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Planetary Atmospheres

Microwave Spectroscopic Studies of Planetary Atmospheres

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Ground-based spectroscopic observations of isotopes of CO in the atmospheres of Mars, Venus, and Titan have been collected over the 1982-1990 period. These observations have been analyzed to obtain information on the photochemistry, dynamics, and thermal profiles of these planetary atmospheres. In the cases of the mesosphere (80-100 km altitude) of Venus and the lower atmosphere (0-70 km altitude) of Mars, the primary conclusion of this research is that significant interannual variations in the global thermal and compositional structures of these atmospheres occur over 10 year periods. The Titan studies have focussed on pinning down the true atmospheric CO abundance. A more detailed summary of the results for each of these planetary atmospheres is provided below.

Mars - Three publications regarding microwave studies of the Mars atmosphere have been completed during the course of this 3 year grant (see accompanying list of publications). We have developed a technique of combining observations of the optically thick  $^{12}\text{CO}$  microwave spectrum with the optically thin microwave  $^{13}\text{CO}$  spectrum to retrieve both the CO mixing ratio and the temperature profile (0-70 km altitude) of the Mars atmosphere. Since we do not resolve the disk of Mars, these measurements refer to low-to-mid latitude average properties of the Mars atmosphere. A comparison of such measurements taken in 1975, 1980, 1982, 1988, 1989, and 1990 leads to two important conclusions. To within the accuracy of the CO mixing determination (~15%), there exists no evidence for the large CO abundance variations proposed by Hunten (1974). We also show that the measurements of 100 % variations in Mars CO by Lellouch et al. (1989) were based on incorrect analysis of their data. Secondly, we show that the Mars atmosphere is much colder for the period corresponding to our microwave observations than was observed during the dusty periods corresponding to Viking and Mariner 9 measurements of the thermal state of the Mars atmosphere. The thermal profiles we derive from the microwave spectra are much more consistent with the radiative-convective profiles calculated for the clear, dust-free Mars atmosphere (Gierasch and Goody, 1968). We conclude that the 1980-1990 period was a period of relatively low dust loading in the Mars atmosphere, which may be more representative of the Mars atmosphere than the conditions observed during Viking and Mariner 9. A complete discussion of

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these results and further implications is provided in Clancy et al. (1990), a much briefer presentation (Clancy and Muhleman, 1990) is included with this report.

**Venus** - Studies of the Venus atmosphere are based on the same technique described above for Mars. However the Venus CO spectra return information on temperatures and CO abundances in the mesosphere of Venus, which is a transition region between the massive zonally rotating lower atmosphere and the upper atmosphere, or cryosphere, in which subsolar-to-antisolar circulation drives extreme thermal and compositional gradients. We find that both the temperatures and global distribution of CO in the Venus mesosphere exhibited dramatic variations over the 1982-1990 period of our observations. These variations can be characterized by a global scale warming of low-to-mid latitude temperatures in the mesosphere between 1984 and 1986, accompanied by factors-of-ten changes in the diurnal gradient of CO mixing ratios. The accompanying preprint (Clancy and Muhleman, 1991) presents the analysis and conclusions of this study in great detail.

**Titan** - New observations of the microwave spectra of CO and HCN in the atmosphere of Titan were obtained in 1989 and 1990. These spectra have been analyzed to provide preliminary results. We obtain a CO abundance which agrees with our previous broadband result (Muhleman et al., 1984). This result is in disagreement with the microwave observations of Marten et al. (1988), but it is in agreement with the infrared observations of Titan CO by Lutz et al. (1983). The HCN profile we measure agrees with the upper stratospheric determination by Tanguy et al. (1990), but our broadband, high frequency (354 GHz) spectrum appears to require that HCN freezes out at a higher altitude in the lower stratosphere than previously thought. These results will be developed in more detail in a forthcoming publication.

#### Publications:

- Clancy, R.T. and D.O. Muhleman, Corrections regarding the Lellouch et al. (1989) analysis of Mars atmospheric  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra, *Icarus*, **85**, 120-129, 1990.
- Clancy, R.T., D.O. Muhleman, and G.L. Berge, Global change in the 0-70 km thermal structure of the Mars atmosphere derived from 1975 to 1989 microwave CO spectra, *J. Geophys. Res.*, **95**, 14,543-14,554, 1990.
- Clancy, R.T. and D.O. Muhleman, Measurements of a cold-clear state for the Martian atmosphere, *Ad. Space. Res.*, submitted, 1990.
- Clancy, R.T. and D.O. Muhleman, Long term (1979-1990) changes in the thermal, dynamical, and compositional structure of the Venus mesosphere as inferred from microwave spectral line observations of  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$ , *Icarus*, in press, 1991.

**Measurements of a Cold-Clear State  
for the Martian Atmosphere**

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## ABSTRACT

An analysis of ground-based microwave spectra of CO in the atmosphere of Mars yields the 0-70 km atmospheric temperature profile for periods of observations in 1975, 1980, 1982, 1988, 1989, and 1990. The derived atmospheric temperatures are ~20K cooler than observed by Viking spacecraft observations in 1976-1977. Seasonal ( $L_s$ ) variations of 20K are apparent (maximum near  $L_s=270^\circ$ ) for atmospheric temperatures up to an altitude of ~50 km. It is inferred that the atmosphere of Mars is often much clearer of dust and colder than indicated by the Viking and Mariner 9 periods of observation during the 1970's.

## INTRODUCTION

Ground-based microwave (1.2-2.6 mm) observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  in the atmospheres of Mars and Venus provide a means to monitor both the global abundance of CO and atmospheric temperatures. Such microwave spectra possess several advantages in terms of their analysis. They are usually self-calibrating in that a well-defined continuum level of microwave emission, due either to surface or broadband atmospheric radiation, accompanies the spectral line absorption/emission within the atmosphere. The spectral line radiative transfer is also relatively straightforward. Atmospheric scattering processes are negligible at microwave frequencies, LTE holds to very low pressures (<nanobar), the source function is very nearly linear with the local temperature, and the lines are typically well separated. Another particularly useful feature of microwave spectral lines in planetary atmospheres is that collisional broadening exceeds thermal broadening for atmospheric pressures  $> 0.1$  mbar. As a consequence, it is possible to retrieve mixing profiles of molecular species from remote, non-limb sounding geometries.

## MICROWAVE CO SPECTRA

Our recent microwave studies of CO in the Mars atmosphere are documented in Clancy, Muhleman, and Berge (1990)/1/. Microwave opacities of the 1.3 mm transition of  $^{12}\text{CO}$  are sufficiently large to provide temperature weighting functions from the surface of Mars to an altitude of 70 km (figure 1). The photochemical lifetime of CO in the Mars atmosphere is long enough ( $>3$  years; e.g., Hunten, 1974)/2/ to ensure that it is vertically well mixed. We measured the optically thin 1.2 mm transition of  $^{13}\text{CO}$  in November of 1988 to determine the CO volume mixing ratio ( $6.0 \pm 1.5 \times 10^{-4}$ ), which was found to be consistent within measurement uncertainties with the 1967 infrared determination ( $8 \pm 2 \times 10^{-4}$ ) by Kaplan et al. (1969)/3/. Figure 2 indicates the observed spectrum of  $^{13}\text{CO}$  with the best-fit synthetic spectrum, corresponding to a CO mixing ratio of  $6 \times 10^{-4}$  and a Mars atmospheric temperature profile (figure 4) consistent with the observed  $^{12}\text{CO}$  spectrum (figure 3). Observations of the  $^{12}\text{CO}$

spectra provide an accurate measure of atmospheric temperatures because they are more sensitive to  $\pm 10\text{K}$  perturbations in atmospheric temperatures (figure 3a) than they are to  $\pm 50\%$  uncertainties in the CO mixing ratio (figure 3b). Lellouch et al. (1989)/4/ performed a similar analysis of microwave  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra observed in 1986-1987, however their analysis was shown to be in error (Clancy and Muhleman, 1990)/5/. Lellouch, Paubert, and Encrenaz (1990)/7/ have since analyzed very high signal-to-noise spectra of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  observed in 1988. Their analysis of these observations indicates a CO mixing ratio of  $8 \pm 2 \times 10^{-4}$ , and that the fall-off in the CO mixing ratio in the lower 10-20 km of the Mars atmosphere as inferred from Phobos ISM observations (Rosenquist et al., 1990)/6/ does not occur on a global scale.

### MARS ATMOSPHERIC TEMPERATURES

Clancy, Muhleman, and Berge (1990) focussed on the derivation of Mars atmospheric temperature profiles (0-70 km) from microwave spectra of  $^{12}\text{CO}$ . The predominant source of uncertainty in such derived temperatures results from  $\pm 5\text{K}$  uncertainties in the solid-body continuum radiation of Mars, which is used to self-calibrate the CO line emission/absorption. CO spectra of the whole-disk of Mars, observed in 1975, 1980, 1982, 1988, and 1989, were analyzed to retrieve low-to-mid latitude average atmospheric temperatures for Mars (figure 4). A basic conclusion from this work is that the Mars atmosphere is colder, and presumably clearer, during all of the periods observed relative to the warm, dusty state of the Mars atmosphere observed by Viking in 1976-1977 and by Mariner 9 in 1971-1972. Although the 1988-1989 temperatures of figure 4 compare well with the Viking profiles, they were measured at a solar longitude ( $L_S$ ) corresponding to 40% increased solar flux relative to the  $L_S$  of the Viking profiles. The 1980 and 1982 microwave temperature profiles, which are 20-40 K cooler than the Viking profile at all altitudes, were measured at roughly the same  $L_S$  as the Viking profiles. In figure 5b, we show the  $L_S$  dependence of 0.5 mbar level ( $\sim 25$  km altitude) atmospheric temperatures inferred from Viking descent observations (Seiff, 1978)/8/, Viking IRTM (Martin, 1981)/9/, and Mariner 9 IRIS radiances (Conrath, 1975)/10/; compared to that exhibited by the microwave observations, including two new 1990 measurements. Both data sets indicate  $\sim 20$  K variations with  $L_S$ , but the microwave temperatures are 20 K cooler overall. Figures 5a and 5c demonstrate that the seasonal ( $L_S$ ) variations and the generally cooler temperatures extend over the 3 mbar ( $\sim 7$ -8 km) to .05 mbar (40-48 km) region. Only the Viking descent and ground-based microwave measurements are included in figures 5a and 5c, since observations comparable to the IRTM  $15 \mu\text{m}$  brightness temperatures are not available to document seasonal variations at these levels.

## CONCLUSION

The cold atmospheric temperatures we infer for Mars have several implications. Colder temperatures are an indicator of much reduced dust loading (Pollack et al., 1979)/11/, and can affect the latitudinal and vertical distributions of atmospheric  $H_2O$  and clouds. Perturbations to atmospheric  $H_2O$  and  $H_2O_2$  may also affect the vertical and latitudinal distributions of atmospheric  $O_3$  (Clancy, Muhleman, and Berge, 1990). Furthermore, the altitude-density profile for the Mars atmosphere changes significantly between the warm-dusty and cold-clear states of the atmosphere. Atmospheric densities for the same  $L_S$  change by as much as a factor-of-three at the 50 km altitude level, between these states. We assert that the Mars atmosphere observed by the Phobos mission was much colder and clearer than observed during the Viking mission; and that such a cold-clear state may be more representative of average conditions within the Mars atmosphere.

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#### FIGURE CAPTIONS

- Figure 1. Nadir temperature weighting functions for the 230 GHz  $^{12}\text{CO}$  line. The various functions correspond to different frequency offsets,  $\nu - \nu_0$ , from the line center. Higher opacities closer to the line center lead to weighting functions which peak at higher altitudes.
- Figure 2. Measured (jagged line) and best-fit (solid line) 230 GHz  $^{13}\text{CO}$  spectra, observed in November of 1988. The best-fit spectrum corresponds to a CO mixing ratio of  $6 \times 10^{-4}$  and the November, 1988 temperature profile presented in figure 4. Dashed lines correspond to  $\pm 1\sigma$  errors of  $\pm 1.5 \times 10^{-4}$  for the CO mixing ratio.

Figure 3. Measured (jagged line) and best-fit (solid line) spectra of the  $J=1 \rightarrow 2$   $^{12}\text{CO}$  transition, observed in November of 1988. Dashed line synthetic spectra correspond to independent perturbations of (a)  $\pm 10\text{K}$  in the solution atmospheric temperature profile; and (b)  $\pm 50\%$  to the CO mixing ratio.

Figure 4. Mid-to-low latitude average temperature profiles for the Mars atmosphere, derived from  $^{12}\text{CO}$  spectra observed in a) May and November of 1988 and January of 1989; and b) November of 1975, March-April of 1980, and January of 1982. A CO mixing ratio of  $6 \times 10^{-4}$ , derived from November, 1988  $^{13}\text{CO}$  spectra, was used to calculate all six of the microwave temperature profiles. A Viking reference profile (Seiff, 1978)/8/ and a radiative convective equilibrium profile (Gierasch and Goody, 1968)/12/ are included for comparison.

Figure 5. Atmospheric temperature, at pressure levels of a) 3.0 mbar; b) 0.5 mbar; and c) 0.05 mbar, versus Mars season ( $L_s$ ). The microwave-derived temperatures are represented by circles, the average of the Viking 1 and 2 lander descent measurements (Seiff, 1978) are presented by squares. For the 0.5 mbar level, the Viking IRTM data (diamonds, Martin, 1981)/9/ are the 15 micron brightness temperatures, averaged over 40S-40N and 10AM-6PM. The Mariner 9 IRIS data are for 9-10AM measurements at 20S-30S latitudes (asterisks; Conrath, 1975)/10/.



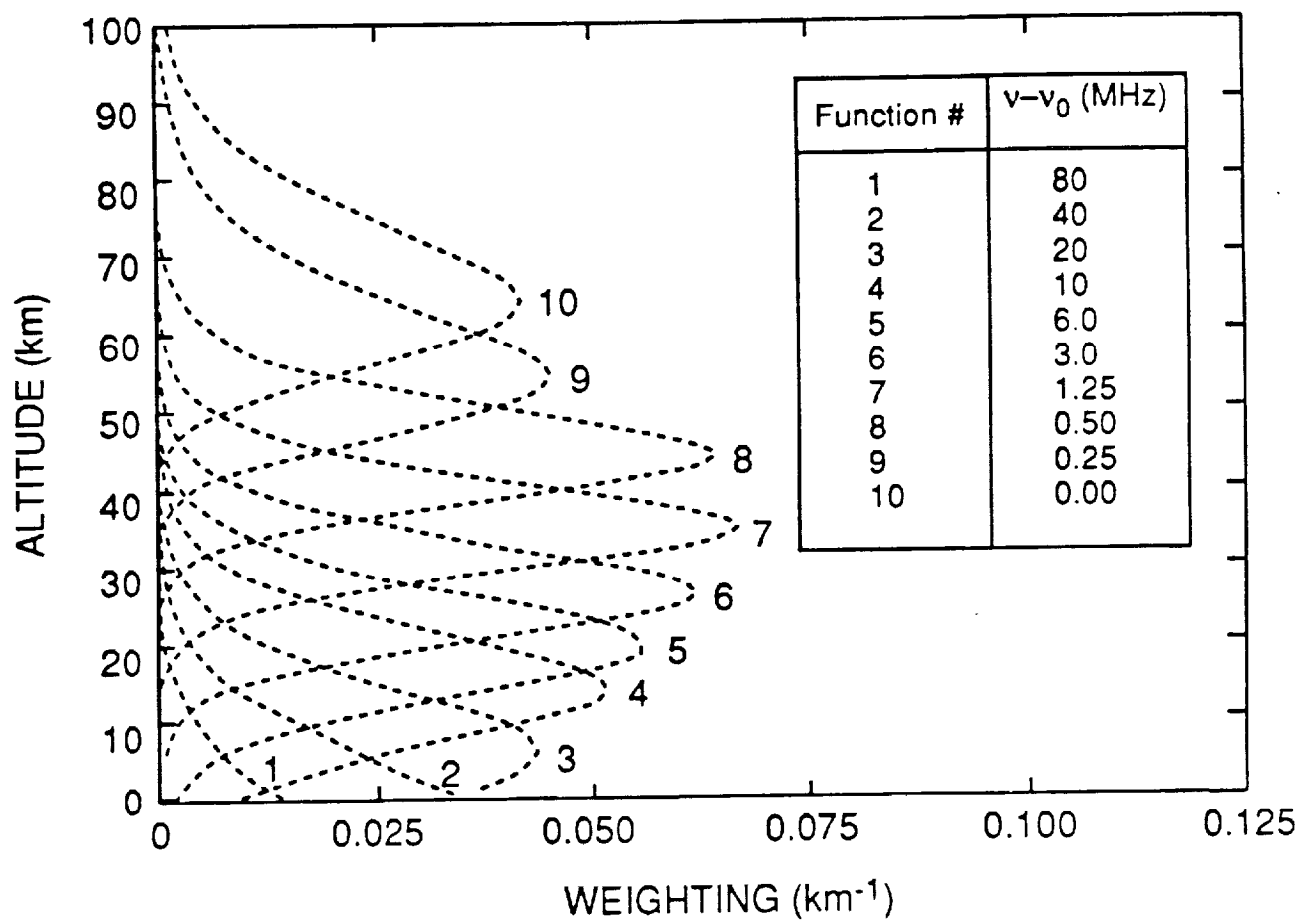


Figure 1

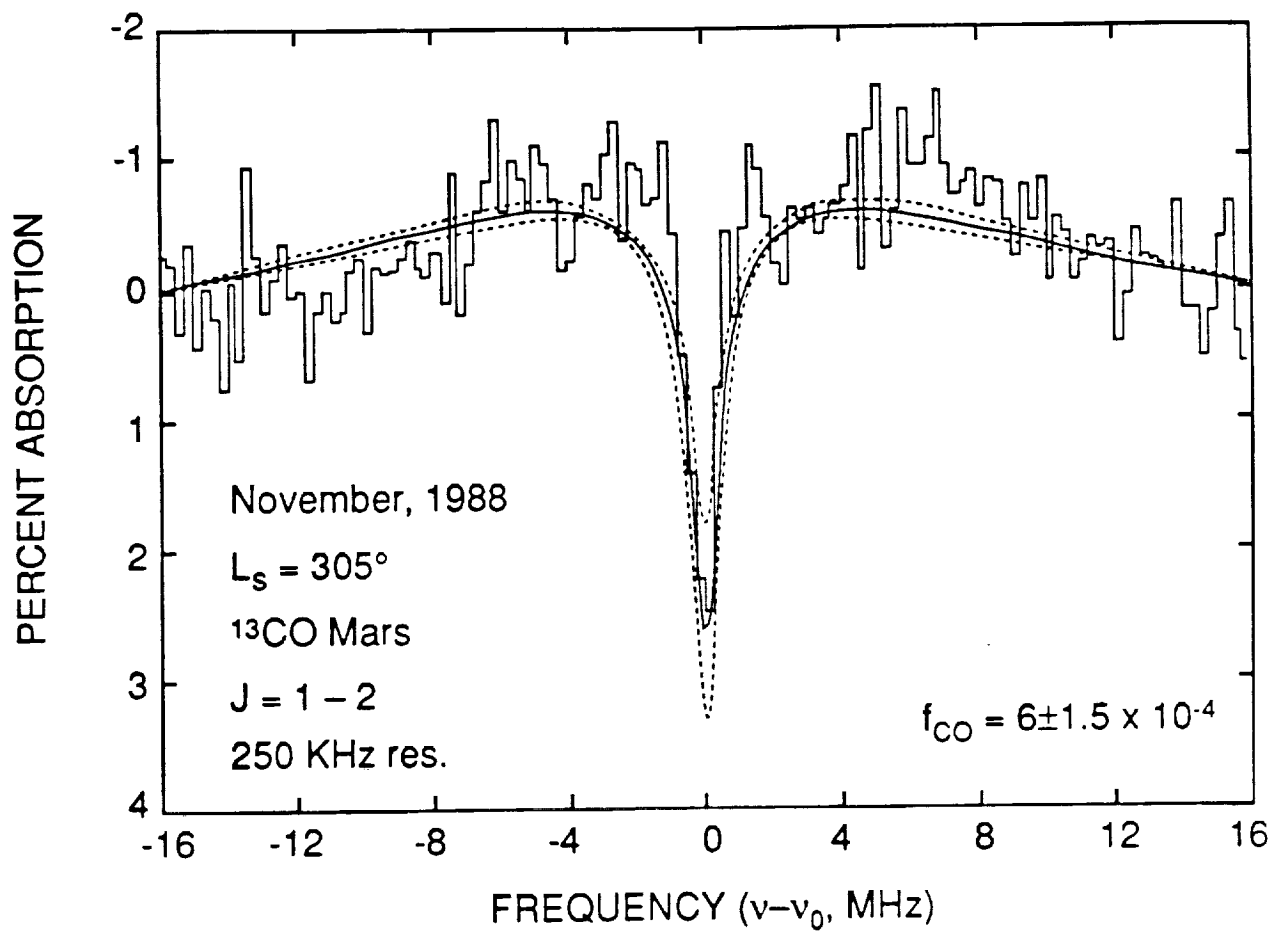


Figure 2

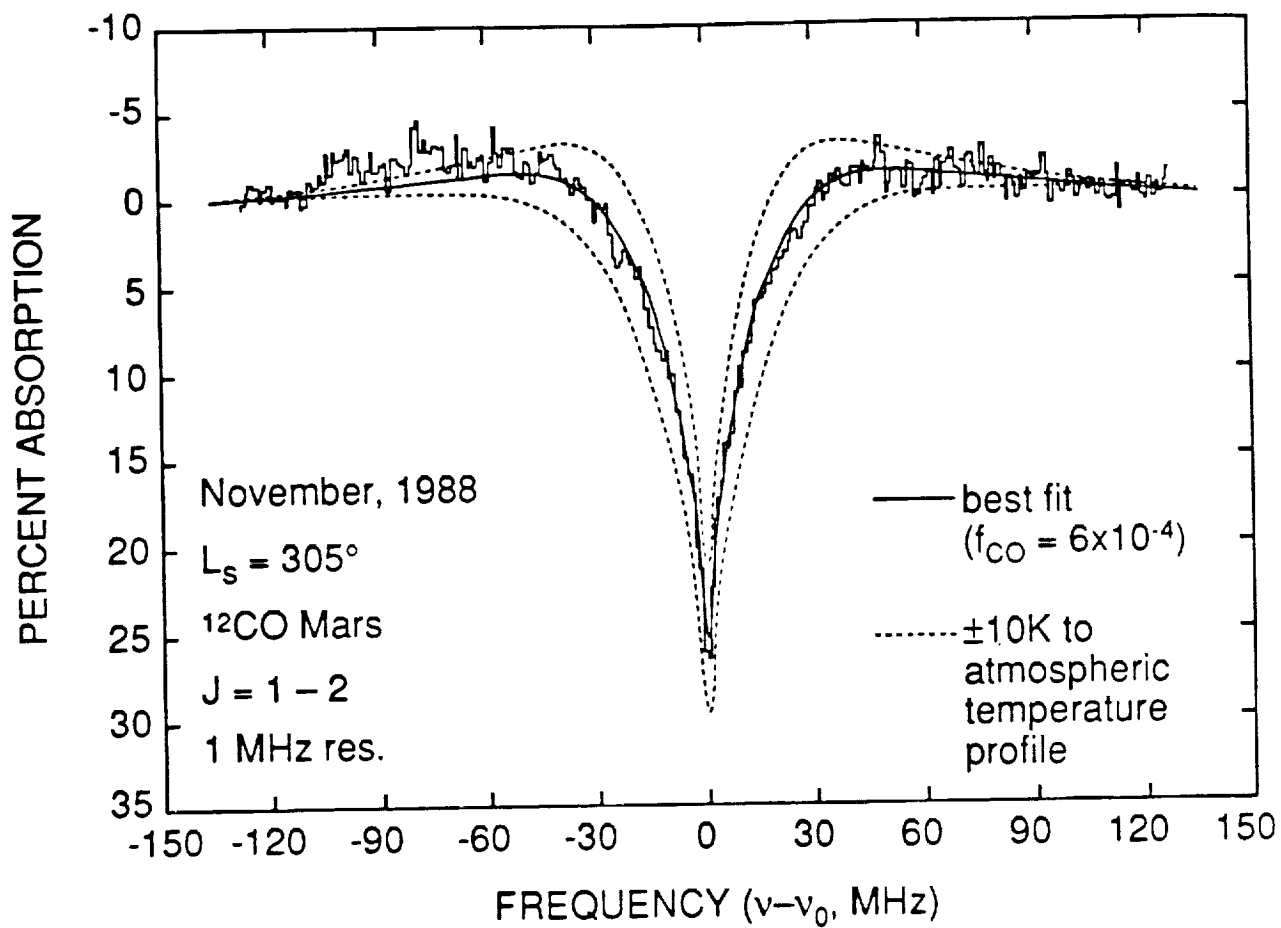


Figure 3a

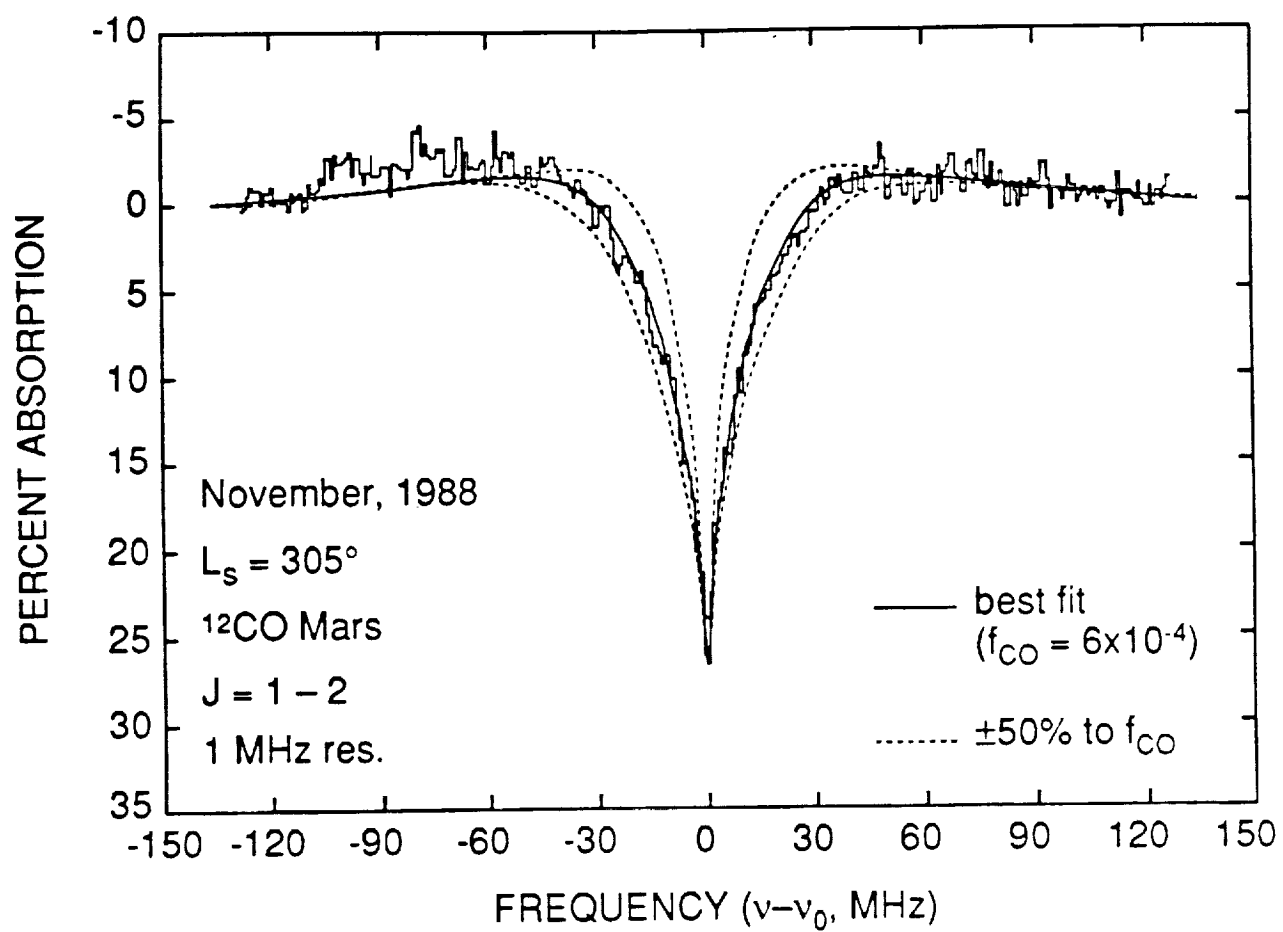


Figure 3b

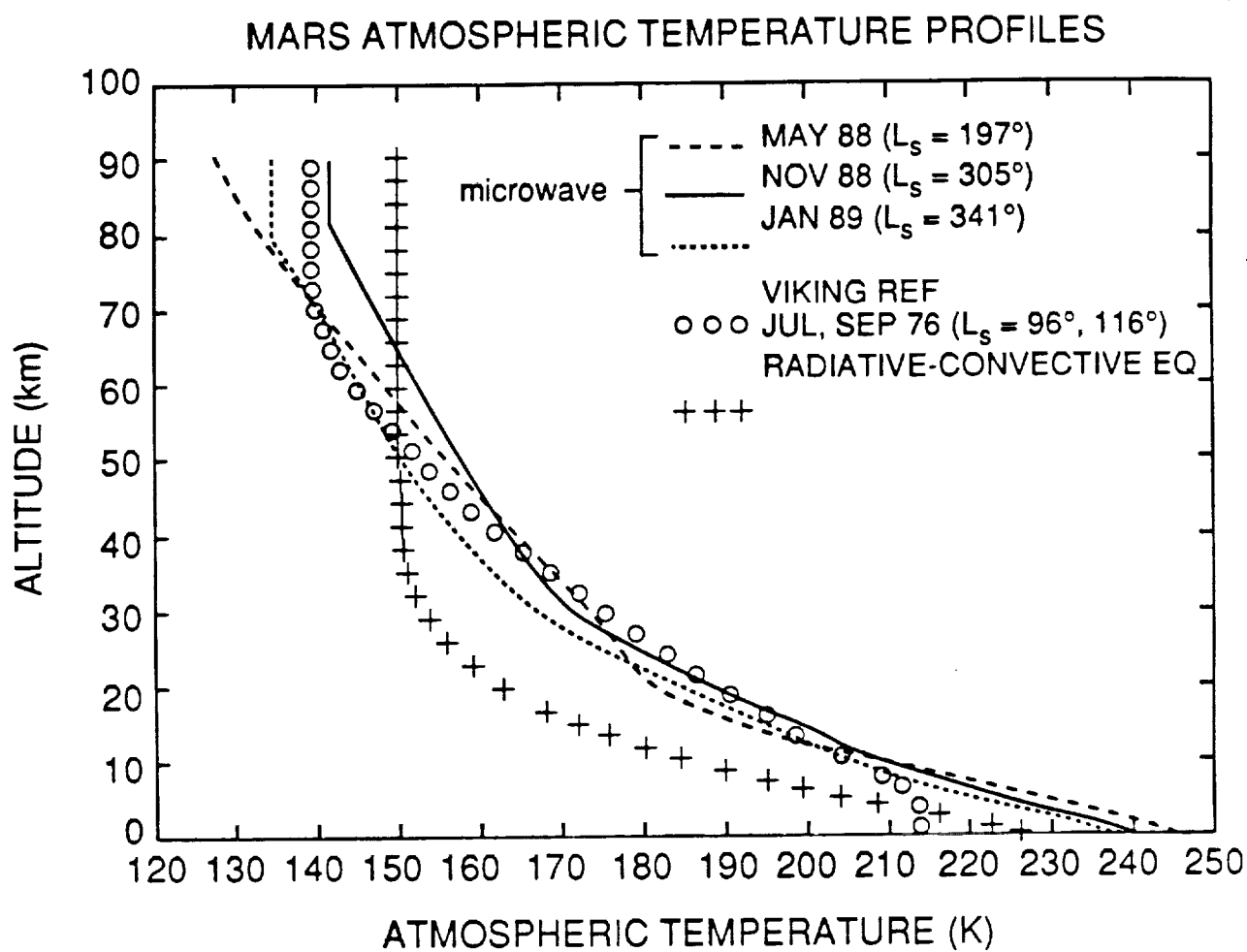


Figure 4a

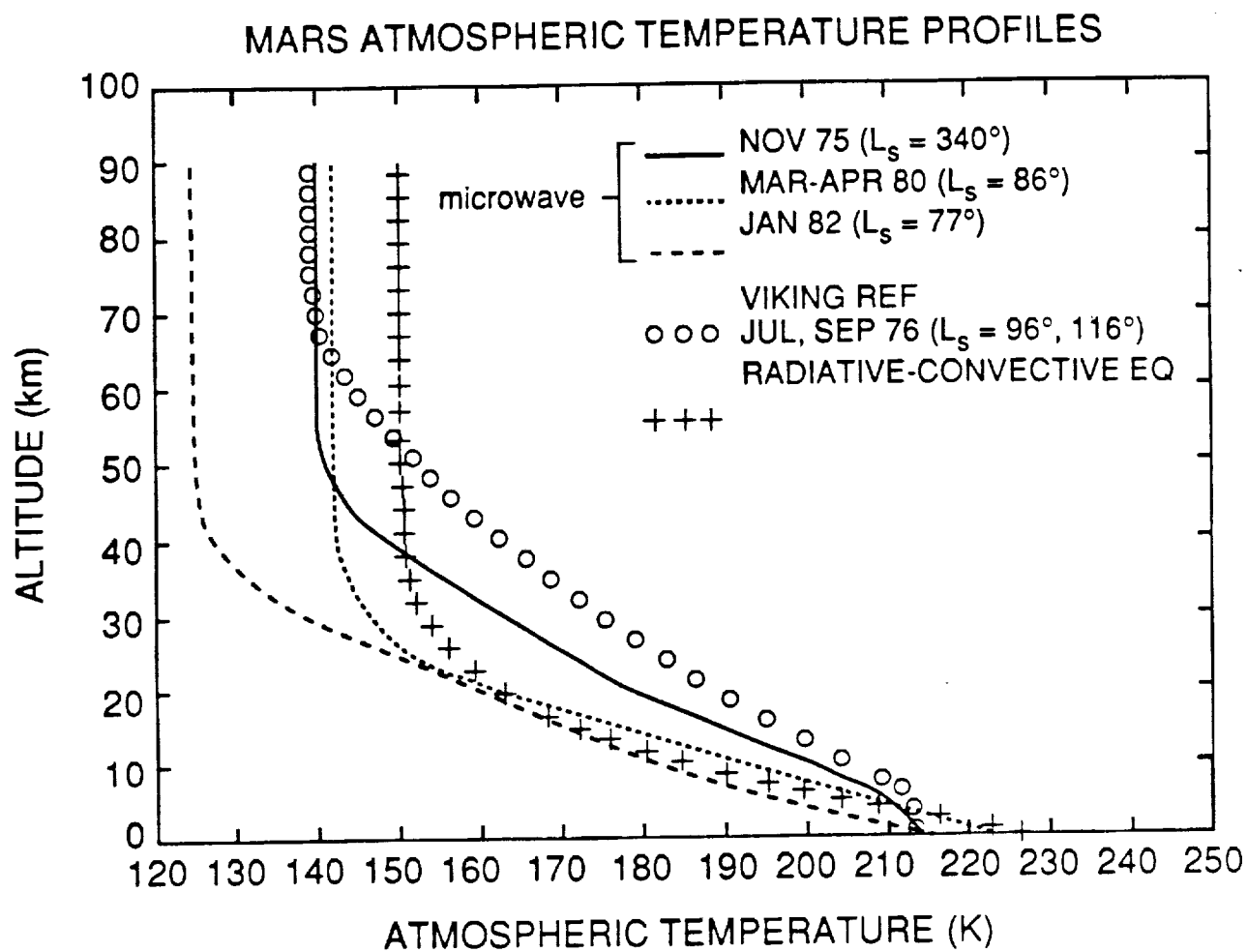


Figure 4b

ATMOSPHERIC TEMPERATURE (K)

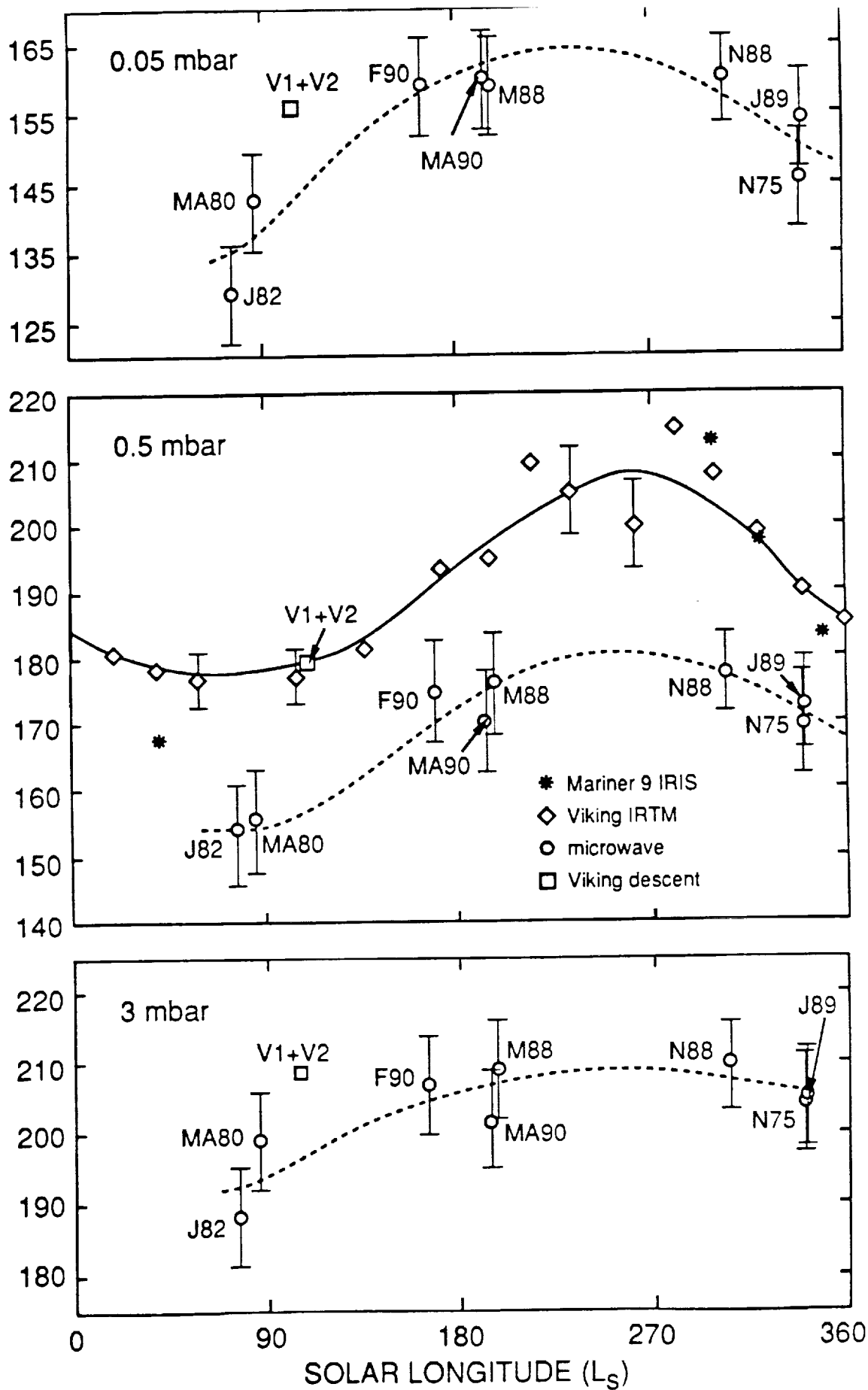


Figure 5

LONG TERM (1979-1990) CHANGES IN THE THERMAL, DYNAMICAL, AND  
COMPOSITIONAL STRUCTURE OF THE VENUS MESOSPHERE AS INFERRED  
FROM MICROWAVE SPECTRAL LINE OBSERVATIONS OF  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  AND  $\text{C}^{18}\text{O}$

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ABSTRACT

Microwave spectral line observations of  $^{12}\text{CO}$  (1.3, 2.6 mm) and  $^{13}\text{CO}$  (1.2 mm) were obtained for Venus near inferior conjunctions in 1982, 1985, 1986, 1988 and 1990. Detailed analyses of these whole-disk spectra were performed to derive low-to-mid latitude average CO mixing profiles (75-105 km) and temperature profiles (85-100 km) for the nightside Venus mesosphere. Mesospheric temperatures determined for the 1982, 1988, and 1990 periods are in good agreement with those returned by Pioneer Venus spacecraft observations in 1979. However, the 1985 and 1986 observations indicate 20-40 K increases in low-to-mid latitude atmospheric temperatures at 85-100 km altitude, relative to the 1979 Pioneer Venus measurements. The 1985-1986 temperature profiles are similar to the mesospheric temperature profile returned by Venera 10 in 1975 (Arduevskiy et al., 1983). Comparisons with 60-90 km temperatures observed between 1978 and 1987 by Pioneer Venus radio occultations (Kliore and Mullen, 1988) indicate a reversal in the latitudinal gradient of atmospheric pressure within the Venus mesosphere in late 1984, early 1985. Cyclostrophic balance appears to persist throughout the Venus mesosphere at this time, as opposed to the breakdown of cyclostrophic balance above 80 km altitude observed by Pioneer Venus in 1979 (Taylor et al., 1980).

Mesospheric CO abundances inferred from the microwave observations also exhibit large changes in 1985-1986. The CO mixing ratio at 80 km altitude increased by several hundred percent between 1982 and 1985. The CO column density above 1 mbar (~86 km) presented a similar increase between 1985 and 1986. Furthermore, the appearance of an extreme solar-zenith-angle gradient in the nightside distribution of mesospheric CO is inferred from the 1986 observations. We suggest that these 1985-1986 perturbations in mesospheric CO and temperatures, the 5-10 year cyclical variations in cloud top dynamics (Del Genio and Rossow, 1989), and the 1979 decay of cloud top  $\text{SO}_2$  (Esposito et al., 1988) are all related phenomena of interannual



variations in the global-scale dynamics within and above the cloud layers of the Venus atmosphere.

We also present a 1.2 mm spectrum of  $C^{18}O$  observed in 1986 which, combined with analysis of the 1986  $^{13}CO$  spectrum, yields a terrestrial ratio ( $5.6 \pm 0.8$ ) for  $^{13}CO/C^{18}O$  in the Venus mesosphere.

## INTRODUCTION

In the following study we present results of an analysis of the nightside Venus mesosphere (defined for our purposes as the 65-110 km altitude region of the Venus atmosphere) based upon microwave CO observations at Venus inferior conjunctions in 1982, 1985, 1986, 1988, and 1990. As described in previous analyses (Schloerb et al., 1980; Wilson et al., 1981; Clancy and Muhleman, 1985a), microwave CO spectra of Venus provide the means to derive the vertical CO mixing profile over the 75-105 km altitude range in the Venus atmosphere. These earlier studies pointed to a significant diurnal variation in the microwave CO line shape and depth, which has been interpreted in terms of the photochemistry and dynamics of the Venus mesosphere (Clancy and Muhleman, 1985b). The present study focuses on interannual variations in nightside mesospheric CO and temperatures. The derivation of mesospheric temperatures over the 85-100 km altitude region is facilitated by measurements of the optically thin  $^{13}CO$  transition at 220.399 GHz combined with the optically thick  $^{12}CO$  transition at 230.538 GHz. A similar technique has been used to yield the 0-70 km altitude profile of temperatures in the Mars atmosphere from ground-based microwave CO observations (Clancy, Muhleman, and Berge, 1990). We also present the first microwave measurement of  $C^{18}O$  (at 219.560 GHz) in a planetary atmosphere, which provides additional constraints on CO isotope ratios within the Venus mesosphere.

The primary results of this study regard significant temporal changes in the thermal and compositional structure of the Venus mesosphere on timescales comparable to

the Venus year. The Venus mesosphere serves as a transitional region between the zonal rotation of the massive lower atmosphere and the solar-zenith-angle symmetric flow of the upper atmosphere, or cryosphere, of Venus. The mesosphere is also a primary photochemical region of the Venus atmosphere. The stability of the  $CO_2$  atmosphere to photolysis into CO and  $O_2$  is maintained via  $CL_2/HO_2$  catalytic cycles within the mesosphere (e.g., Sze and McElroy, 1975; Yung and DeMore, 1982), as is the recycling of  $SO_x$  compounds into cloud-forming  $H_2SO_4$  (Winick and Stewart, 1980; Yung and DeMore, 1982). A complex coupling between photochemistry and dynamics involves photolysis on the dayside, vertical transport via eddy mixing, day-to-night transport forced by diurnally variable solar heating (Dickinson and Ridley, 1975), and the upward extension of zonal rotation into the mesosphere (Clancy and Muhleman, 1985b). Previous indications for long-term variability just below the lower boundary of the mesosphere include a global decay of the  $SO_2$  mixing ratio in early 1979 (Esposito et al., 1988) and 5-10 year cyclic behavior in the mean zonal winds of the cloud top region (65-70 km; Del Genio and Rossow, 1989).

## MICROWAVE OBSERVATIONS

All of the observations presented below were obtained at the NRAO millimeter observatory at Kitt Peak, Arizona<sup>1</sup>. With the exception of the January 1982 data, all of the observations were conducted with the reconstructed 12 meter antenna at the NRAO Kitt Peak facility. The 1982 spectra were taken using the earlier 11 meter antenna and are the only data presented in this analysis which have been previously published (Clancy and Muhleman, 1983). At the 1.3 and 2.6 mm wavelengths of observation, the angular resolution (~30 and 60 arcseconds, respectively) is effectively matched to the angular dimension of Venus near inferior conjunction (40-60 arcseconds).

<sup>1</sup> Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

## Spectral Line Observations

A summary of the observations presented in this analysis is provided in table 1, including relevant measurement parameters for each observation. Observations were not obtained for the 1983 inferior conjunction when the Kitt Peak telescope was under reconstruction. This conjunction also occurred in the middle of the summer, a season for which the Kitt Peak NRAO facility is closed. We obtained spectra of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  near each of the inferior conjunctions of Venus for the years listed in table 1. A  $\text{C}^{18}\text{O}$  spectrum at 1.2 mm was also observed in 1986. With the exception of 1982 when a 2.6 mm receiver was not available, we observed both rotational transitions (2.6 and 1.3 mm) of  $^{12}\text{CO}$ . Combined measurements of the 1.2 mm transition of  $^{13}\text{CO}$  and the 2.6 and 1.3 mm transitions of  $^{12}\text{CO}$  provide two orders-of-magnitude range in the line center optical depths of CO in the Venus mesosphere ( $\tau \sim .05$ -.10, 0.5-1.0, and 4.0-8.0, respectively).

The filter bank spectrometers at Kitt Peak are typically set up as 256 contiguous channels of a given frequency width. We consistently selected 1 MHz and 250 KHz filter widths for the 1.3 mm  $^{12}\text{CO}$  line. This allowed measurement of the strong line "wings" of this transition, corresponding to collisionally broadened CO absorption in the 10-0.1 mbar (75-95 km) region of the Venus atmosphere; and measurement of the doppler width of the line center, corresponding to thermally broadened CO absorption in the .1-.01 mbar (95-105 km) region of the Venus mesosphere. The  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  transitions at 1.2 mm were observed with filter widths of 250 and 100 KHz, since CO absorptions in the "wings" of these lines are too small to measure reliably. Intermediate and variable filter resolutions were chosen for the 2.6 mm  $^{12}\text{CO}$  line over the 1985-1990 period of observations. We have removed linear baselines from all of the microwave spectra presented in this study. In every case, the linear gradient superimposed on the microwave continuum of Venus proved to be quite small (a few per cent).

Consequently, our analysis refers to global average properties of the Venus nightside mesosphere. More specifically, we measure the low-to-mid latitude average properties since 90% of the projected area of the Venus disk refers to latitudes within 50 degrees of the Venus equator.

## Observing System

The observing system has changed somewhat over the 1982-1990 period of the measurements as improvements are continuously implemented at the NRAO Kitt Peak facility. Several constant features include single sideband (SSB) receivers at the  $J=0 \rightarrow 1$  (2.6 mm) transition of  $^{12}\text{CO}$  and double sideband (DSB) receivers at the  $J=1 \rightarrow 2$  (1.2-1.3 mm) transitions of  $^{13}\text{CO}$ ,  $\text{C}^{18}\text{O}$  and  $^{12}\text{CO}$ ; filter bank spectrometers with channel widths ranging from 2 MHz to 100 KHz; and the operation of a corner cube interferometer to reduce the influence of standing waves in the 1.2-1.3 mm observations. The standard observing method was position switching, although observations after 1986 also incorporated beam switching via a nodding subreflector. A Schottky diode receiver was employed for all of the 1.2 mm observations of  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  and the 1.3 mm observations of  $^{12}\text{CO}$ ; and, except in 1982, was characterized by a 500 K SSB receiver noise temperature ( $T_{\text{rec}}$ ) and a 3 GHz sideband separation. The Schottky diode receiver used in 1982 exhibited a larger noise temperature ( $T_{\text{rec}}=1000$  K) and a larger sideband separation (9.5 GHz). The 1985 2.6 mm spectrum of  $^{12}\text{CO}$  was measured with a Schottky diode receiver ( $T_{\text{rec}}=350$  K); an SIS receiver ( $T_{\text{rec}}=120$  K) was used for observations of the 2.6 mm spectrum of  $^{12}\text{CO}$  after 1985. We also note that the 1.2-1.3 mm observations were facilitated by the addition of a second, identical and simultaneously operated Schottky diode receiver (to measure the orthogonal polarization) in 1986.

## Calibration

The procedure employed for the calibration of all of our microwave CO spectra does not require absolute calibration of spectral brightness temperatures. Rather, we calculate line-to-continuum ratios in which the line absorption is shown as a fraction of the continuum signal present in the "wings" of the measured spectrum. This allows an accurate measurement of the CO line emission/absorption relative to the continuum emission of the lower atmosphere (due primarily to pressure induced CO<sub>2</sub> opacity, see below). In this manner we remove the considerable uncertainties in the antenna efficiency, atmospheric transmission, and beam filling factor, which equally affect the continuum and CO line emissions of Venus. Two minor caveats apply to the accuracy of these line-to-continuum ratios. Firstly, we are required to model the very weak CO emission/absorption which is present in the "continuum" level of our spectra, since we do not measure the spectral baselines far enough from the CO transition to completely avoid contribution from CO emission/absorption. Secondly, we note that the DSB 1.2-1.3 mm spectra contain the continuum emission of Venus in both sidebands whereas the CO line is contained in only one sideband. We multiply the 1.2-1.3 mm line-to-continuum ratios by 2.0 to correct for the double sideband. This assumes that the measurement sensitivity is identical for the two receiver sidebands, which is consistent with a well-tuned receiver. We assessed the accuracy of this assumption in 1986, 1988, and 1990 by observing with the <sup>12</sup>CO, C<sup>18</sup>O and <sup>13</sup>CO lines alternately placed in the upper and lower sidebands. In each case the upper and lower sideband measurements produced identical line-to-continuum ratios. Further discussion regarding the double sideband correction can be found in Clancy, Muhleman and Berge (1982).

## ANALYSIS

Radiative transfer analysis of microwave spectra is greatly simplified due to the unimportance of scattering processes. Furthermore, emission is linearly proportional to the physical temperature of the emitting medium at microwave frequencies; and the CO rotational transitions are single, isolated lines at microwave frequencies. Hence, the vertical integration of CO emission/absorption within the Venus mesosphere is a relatively straightforward calculation. Key elements in such modelling include the pressure/thermal broadened lineshape (Voigt lineshape), the integrated line intensity of the CO molecule, and the pressure-temperature and CO mixing profiles of the Venus mesosphere. Details regarding the CO absorption coefficient and the radiative transfer problem can be found in Clancy and Muhleman (1985a) and Clancy, Jakosky, and Muhleman (1983). We outline below the newer aspects of the radiative transfer treatment incorporated in this analysis.

## Microwave Continuum

As detailed in Muhleman et al. (1979), the microwave continuum of Venus originates from CO<sub>2</sub> broadband emission in the lower atmosphere. An additional source of broadband microwave opacity may be contributed by H<sub>2</sub>SO<sub>4</sub> below the main cloud layers in the Venus atmosphere (Stiefler et al., 1990). However, the 1-3 mm continuum emission of Venus originates within the main cloud layer of Venus (50-60 km). We have used the Muhleman et al. model to calculate the disk brightness temperatures and limb darkening curves at 1.3 and 2.6 mm (Clancy and Muhleman, 1985a). A comparison of the measured continuum spectrum of Venus to our model continuum disk temperatures is also presented in Clancy and Muhleman (1985a). In our current analysis we adopt slight modifications to these 1.3 and 2.6 mm continuum temperatures; at 1.3mm (2.6mm) we now use a continuum temperature of 288 K (335 K) versus the value of 280 K (318 K) used in Clancy and Muhleman (1985a). These newer values

provide a better relative fit to our 1.3 and 2.6 mm CO spectra. The 8-17 K increase in continuum temperatures implied by these changes are roughly equivalent to the 5% uncertainties we estimate for the 1-3 mm continuum temperatures of Venus.

### Three Dimensional Modelling

We perform a vertical integration of CO emission/absorption over the 65 to 139 km altitude range. The lower boundary radiation field is given by the above-described limb darkening profile of microwave continuum temperatures. The separation of the lower boundary continuum radiation from the CO line formation region is appropriate because the CO<sub>2</sub> continuum opacity decreases as the square of the CO<sub>2</sub> density ( $\tau_{\text{CO}_2} < 0.1$  above an altitude of 70 km), and the CO absorption decreases rapidly below 80 km altitude due the pressure dependence of the CO linewidth and the rapid decrease in the CO mixing ratio below 80-90 km.

As the observed spectra correspond to CO emission/absorption over the entire observable hemisphere of Venus, it is necessary to calculate vertically integrated spectra for an area-weighted distribution of path lengths in the Venus atmosphere. Furthermore, the vertical mixing profile of CO and the atmospheric temperature profile above ~100 km altitude are known to exhibit solar-zenith-angle variations. Although our whole-disk spectra do not generally discriminate such variations, it is appropriate to include these global variations in our model to account for the variable local time of the sub-Earth point among the 1982-1990 set of observations. In fact, it proves necessary to incorporate extreme solar-zenith-angle variations in the CO mixing profile in order to fit the 1986 observations. Hence, we have constructed a two-dimensional grid (latitude and local time on Venus) of integration points over the observable hemisphere of Venus at which the CO mixing and temperature profiles are individually specified. The atmospheric temperature profile is specified as a day or night profile according to illumination of Venus at the time of the observation. We assume a day/night

divergence of atmospheric temperature above ~100 km as observed by the Pioneer Venus descent probes (Self and Kirk, 1982). Since the contribution of CO absorption/emission above 100 km is minor except very near the limb of the planet, the diurnal variation of the temperature profile does not impact the synthesis of whole-disk CO microwave spectra significantly.

The latitude/local time grid employed in the two-dimensional integration exhibits 10 degree (40 minute) resolution across the disk, and incorporates atmospheric limb emission over the 75-130 km altitude range. This last component, which was not included in our previous Venus modelling (Clancy and Muhleman, 1983; Clancy and Muhleman, 1985a), is assumed to be latitudinally invariant due to the computational complexity of combining limb emission with a two-dimensional disk integration. We do, however, calculate separate spectra for the east and west limbs of Venus, which incorporate morning/evening asymmetries in the atmospheric temperature and CO mixing profiles. The effect of atmospheric limb emission is not as important for Venus CO spectra as it is for Mars CO spectra (Clancy and Muhleman, 1990). Nevertheless, accurate modelling does require its inclusion. In particular, the depth of 1.2 mm <sup>13</sup>CO line absorption is overestimated by ~20 % when atmospheric limb emission is not included. The effect is much smaller (~2 %) for the deeper <sup>12</sup>CO absorption lines.

The two-dimensional grid of spectral line calculations is summed with weights corresponding to the projected area of the element and the gaussian beam of the Kitt Peak telescope. We assume half-power-full-widths of 60 and 30 arcseconds for observing wavelengths of 2.6 and 1.3 mm, respectively.

### CO-Temperature Sounding

Combined observations of the <sup>12</sup>C and <sup>13</sup>C isotopes of CO provide a practical method of obtaining coincident, optically thick and thin line opacities in the Venus mesosphere. In figure 1, we show temperature weighting functions for the 1.3 mm

$^{12}\text{CO}$  transition at an air mass  $[1/\mu, \mu = \cos(\text{solar zenith angle})]$  of two in the Venus atmosphere. The line center optical depth is  $\sim 10$  for this viewing geometry and assumed CO mixing profile (from figure 8d). Note that the optimum temperature weighting, near the  $^{12}\text{CO}$  line center, falls in a region of the Venus mesosphere which is roughly isothermal. As a result, the  $^{12}\text{CO}$  line center depth is not overly sensitive to the CO mixing ratio in the 90-105 km altitude range. A 270 % increase in the CO mixing ratios near 100 km altitude moves the weighting functions upward one scale height, yet only changes the observed line center brightness temperatures by  $\sim 10$  K (or the line-to-continuum ratio by  $\sim 3\%$ ). Of course, these changes are determined by the true Venus temperature profile; the brightness temperature within the 1.3 mm line center is effectively equal to the temperature of the Venus atmosphere averaged over the 90-105 km altitude range.

Line opacities for the 1.3 mm  $^{12}\text{CO}$  transition fall below unity at 2-4 MHz from line center, depending on the CO mixing profile and the viewing geometry. Within the optically thin regions of microwave CO lines, the depth of absorption becomes much more sensitive to CO variations relative to temperature variations. The observed line depth scales roughly as

$$(F_{\infty}/T_c^2)(T-T_c)/T_c$$

where  $F_{\infty}$  is the CO mixing ratio,  $T$  is atmospheric temperature, and  $T_c$  is the microwave continuum temperature of Venus. The inverse temperature squared dependence reflects the temperature dependence of the line absorption coefficient. Under optically thin conditions and  $T-T_c \gg 1\text{K}$ , the observed line depth exhibits comparable sensitivities to the CO abundance and atmospheric temperature. In practice the weighting function for  $^{12}\text{CO}$  line absorption at 10 MHz from line center (figure 1) provides a more useful measure of the CO mixing ratio near 80 km than it does for

temperature, since uncertainties in the CO mixing profile ( $\geq 25\%$ ) are expected to be much larger than uncertainties in the temperature profile ( $< 10\%$ ) in this region.

Opacities at the 1.2 mm  $^{13}\text{CO}$  transition are much less than unity even at the line center. The line-center weighting function for the 1.2 mm transition of  $^{13}\text{CO}$  is included in figure 1 and has been scaled by a factor-of-five to enhance its visibility in the figure. The 1.2 mm  $^{13}\text{CO}$  line depth provides a good measurement of the CO mixing ratio at 90-100 km altitude and, as such, is complementary to the 1.3 mm  $^{12}\text{CO}$  temperature sensitivity in this altitude region. The 2.6 mm  $^{12}\text{CO}$  line opacity is near unity at the very line center. As a result, it primarily constrains CO mixing ratios in the 90-100 km altitude region, but still exhibits increased sensitivity to atmospheric temperatures in the same region. Absorption in the line wings of the 2.6 mm  $^{12}\text{CO}$  transition allows a separate measure of the CO mixing profile in the 80-90 km region.

#### CO Isotopes

An assumption implicit in combining  $^{12}\text{CO}$  and  $^{13}\text{CO}$  opacities to sound the temperature and CO mixing profiles of the mesosphere is that the isotope ratio  $^{12}\text{CO}/^{13}\text{CO}$  is well known. In an earlier analysis of the 1982 observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$ , we arrived at the conclusion that the  $^{12}\text{CO}/^{13}\text{CO}$  ratio in the Venus mesosphere was  $185 \pm 69$  (Clancy and Muhleman, 1983), indicating a  $^{12}\text{CO}/^{13}\text{CO}$  ratio 1.4 sigma above the terrestrial value of 89. Such a ratio is inconsistent with the ground-based infrared spectroscopic observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  by Combes et al. (1968) and the Pioneer Venus mass spectroscopy measurements of  $^{12}\text{CO}_2$  and  $^{13}\text{CO}_2$  by Hoffman et al. (1980), both of which indicate terrestrial ratios for  $^{12}\text{C}/^{13}\text{C}$  in the Venus atmosphere. These determinations refer to the cloud top region and the lower atmosphere of Venus, respectively; which led Clancy and Muhleman (1983) to conclude that any non-terrestrial fractionation of CO isotopes must be restricted to the upper atmosphere of Venus.

## OBSERVATIONAL RESULTS

The large errors in  $^{12}\text{CO}/^{13}\text{CO}$  associated with the Clancy and Muhleman analysis resulted from a combination of modelling and measurement uncertainties. Key model assumptions were the atmospheric and continuum temperatures of Venus which differentially affect  $^{13}\text{CO}$  and  $^{12}\text{CO}$  line absorptions, since the  $^{12}\text{CO}$  line is optically thick and the  $^{13}\text{CO}$  line is not. The large line center opacity of the 1.3 mm  $^{12}\text{CO}$  line also introduced increased uncertainty in the CO mixing profile at 95 km, since this line was used to constrain the CO mixing profile in the analysis. In the present analysis we find that adjustments to the temperature and CO mixing profiles of the Venus mesosphere and changes in the adopted microwave continuum of Venus (as discussed above) allow good fits to the 1982  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra with a terrestrial ratio for  $^{12}\text{CO}/^{13}\text{CO}$ . Furthermore, the 1985-1990 observations of  $^{12}\text{CO}$  (1.3 and 2.6 mm) and  $^{13}\text{CO}$  do not support a value of 185 for  $^{12}\text{CO}/^{13}\text{CO}$ .

In order to provide a more direct measurement of CO isotope ratios in the Venus mesosphere, we observed the  $\text{C}^{18}\text{O}$  microwave absorption along with  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines in 1986. A comparison of the  $\text{C}^{18}\text{O}$  and  $^{13}\text{CO}$  lines, both of which are optically thin, provides a much better measurement of isotope ratios, particularly when combined with 1.3 and 2.6 mm observations of  $^{12}\text{CO}$ . After deriving the temperature and CO mixing profiles from fitting of the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra (as discussed below, see figures 2-6), we find that a terrestrial ratio for  $^{13}\text{CO}/\text{C}^{18}\text{O}$  provides an adequate fit to the observed  $\text{C}^{18}\text{O}$  spectrum (figure 4f). We conclude that  $^{13}\text{CO}/\text{C}^{18}\text{O}$  is terrestrial to within the uncertainties of our analysis ( $\pm 15\%$ ), and infer that  $^{12}\text{CO}/^{13}\text{CO}$  is also terrestrial.

The standard method of analysis employed in this study is to calculate synthetic spectra of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  which best fit the observed spectra. The two key model inputs, the temperature and CO mixing profiles, are iteratively adjusted to provide the optimum fits. Uncertainties in the solutions for these profiles are generated by model-data comparisons incorporating altitude-dependent perturbations to temperatures and CO mixing ratios. Two additional parameters are derived from the 1986 observations, the isotope ratio  $^{13}\text{CO}/\text{C}^{18}\text{O}$  and a measure of the nightside distribution of CO at altitudes of 90-105 km.

### January, 1982

We show fits (dashed lines) to the 1982 observations (solid lines) of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  in figure 2, which includes .25 and 1 MHz resolution 1.3 mm spectra of  $^{12}\text{CO}$  and a 100 KHz resolution 1.2 mm spectrum of  $^{13}\text{CO}$ . We were not able to observe the 2.6 mm spectrum of  $^{12}\text{CO}$  at this time. The measurement uncertainties of the  $^{12}\text{CO}$  spectra are dominated by baseline fluctuations due to receiver gain variations and standing waves. Channel-to-channel noise, which reflects the system noise level and the integration time/channel width product, is typically small as compared to baseline fluctuations in all of  $^{12}\text{CO}$  spectra we present. In our error analysis of fits to the  $^{12}\text{CO}$  spectra, we adopt measurement uncertainties corresponding to the observed 1-3 % baseline fluctuations. The signal-to-noise ratios for the much weaker  $^{13}\text{CO}$  spectra are increasingly affected by channel-to-channel noise, since the observed bandwidths and channel widths of these spectra are much reduced relative to the  $^{12}\text{CO}$  spectra. The spectral wavelengths of the baseline fluctuations are typically larger than the entire  $^{13}\text{CO}$  bandpass (c.f., figure 3a and 3c).

Figure 7 presents the 1982-1990 temperature profiles (vs. altitude in figure 7a, and vs. pressure in figure 7b) that provide the best-fit synthetic spectra presented in figures

2-6. The 1982 temperature profile of figure 7 compares favorably to the Pioneer-Venus derived CIRA reference profile for latitudes  $< 30^\circ$ , as indicated by the squares in figure 7. The relative uncertainty among the 1982-1990 microwave determinations of the temperature profile is indicated on the 1985 temperature profile. The  $\pm 8$  K one-sigma relative error bars near an altitude of 95-100 km correspond to uncertainties of  $\pm 2.5\%$  for the line center depths of the 1.3 mm  $^{12}\text{CO}$  spectra of figures 2-6. The temperature error due to uncertainty in the CO mixing ratio is minor in the altitude range 95-100 km, but increases below 95 km (see discussion above) and leads to increasing temperature uncertainties at altitudes below 95 km. Temperature uncertainties increase above 100 km as the line center weighting does not extend significantly above 105 km (see figure 1). The absolute uncertainties in the microwave temperature profiles are largely due to uncertainty in the 1.3 mm continuum temperature of Venus, which we estimate to be  $\pm 15$  K. Hence, we estimate  $\pm 15$  K uncertainties in the absolute scale of the microwave temperature profiles.

The CO mixing profile determined from the 1982 observations is presented in figure 8a. The multiplicity of CO mixing profiles above 90 km altitude indicates the solar zenith-angle dependence in the CO mixing profile which is modelled for the visible nightside hemisphere of Venus. With the exception of 1986, we assume a nightside CO "bulge" centered on the equator at midnight. The maximum CO mixing ratios are for a local time of 12 AM, minimum CO mixing ratios correspond to a local time of 6 PM and 6 AM. The magnitude and solar-zenith-angle dependence of the CO variation are based upon chemical-dynamical modelling (Dickinson and Ridley, 1975) and previously observed phase variations in whole-disk CO spectra (Clancy and Muhleman, 1985a). Our 1982  $^{12}\text{CO}$  and  $^{13}\text{CO}$  observations do not provide adequate information to constrain CO variations over the Venus nightside. Diurnal CO variations are modelled for the 1982, 1985, 1988, and 1990 observations to provide comparison to the 1986 results, which require an extreme solar-zenith-angle variation in CO above 90

km to fit the 2.6 mm  $^{12}\text{CO}$  and 1.2 mm  $^{13}\text{CO}$  spectra simultaneously. We stress that all of the years except 1986 can be fit with diurnally invariant CO mixing profiles or diurnally varying CO mixing profiles consistent with previous phase-dependent observations of Venus (Clancy and Muhleman, 1985a).

One-sigma uncertainties in the CO mixing profile are indicated by error bars in figures 8a-e. Minimum uncertainties of  $\pm 25\%$  exist in the 85-95 km altitude region, and are due to spectral baseline fluctuations in the 1.3 and 2.6 mm  $^{12}\text{CO}$  spectra and uncertainty in the Venus continuum temperature. The uncertainties increase as the CO mixing ratios decrease below 85 km altitude (see figure 8), since the absorption at frequencies  $> 10$  MHz from line center is decreased relative to the baseline fluctuations. At altitudes above 95 km, the contribution of CO absorption to the line center depth becomes increasingly smaller. Notice that the CO mixing profile above 95 km is more uncertain for the 1982 period relative to the other periods because a 2.6 mm  $^{12}\text{CO}$  spectrum was not observed in 1982.

#### March, 1985

Figures 3a-d present the observed and fitted spectra for the 1985 inferior conjunction of Venus. As for the other periods of observation, the sub-Earth local time on Venus and the illuminated fraction of the disk of Venus are indicated in the figures. With the exception of the 1982 observations, the sub-Earth local time is not midnight. Scheduling of observations exactly at inferior conjunction places Venus too near the Sun to conform to operational constraints on the new NRAO telescope. Except for 1982, we observed Venus 3-5 weeks before (1985, 1988) or after (1986, 1990) inferior conjunction. In all cases the dayside fraction of Venus observed was less than 30%. As noted above, we incorporate the variable local time of the sub-Earth point in our modelling. We also consider the observational effects of variable local times in the discussion of our results.

Description of the observed and fitted spectra is the same as indicated for the 1982 spectra of figures 2a-d. However, we have included additional synthetic spectra for the 1.3 mm  $^{12}\text{CO}$  presentations (solid lines, figures 3a and 3b) to indicate the expected 1.3 mm  $^{12}\text{CO}$  absorption for a Pioneer-Venus temperature profile. The best-fit temperature profile, indicated in figures 7a and 7b, exhibits 30-40 K warmer temperatures than those observed in 1979 by Pioneer-Venus over the 85-100 km altitude region. The 1.3 mm  $^{12}\text{CO}$  absorption corresponding to a Pioneer-Venus temperature profile was calculated for a CO mixing profile consistent with fits to the 2.6 mm  $^{12}\text{CO}$  spectrum (figure 7c) and the 1.2 mm  $^{13}\text{CO}$  spectrum (figure 7d), and is clearly inconsistent with the observed 1.3 mm  $^{12}\text{CO}$  spectra (figures 7a and 7b). Reductions in the CO mixing ratios necessary to fit the 1.3 mm  $^{12}\text{CO}$  with a Pioneer-Venus temperature profile are large (a factor of  $\sim 10$  at altitudes of 90-100 km) and unphysical since they would require the CO mixing ratio to decrease at altitudes above 90 km. Such changes to the CO mixing profile also underestimate the 2.6 mm  $^{12}\text{CO}$  and 1.2 mm  $^{13}\text{CO}$  line depths by factors of 2-5.

The CO mixing profiles determined from the 1985 observations are presented in figure 8b. The diurnal variation incorporated for CO mixing above 90 km is reduced relative to that shown for 1982, 1988, and 1990. A smaller nighttime gradient in the CO mixing ratio allows optimum combined fits to the 2.6 mm  $^{12}\text{CO}$  and 1.2 mm  $^{13}\text{CO}$  spectra (see discussion of 1986 observations). This result is, however, statistically significant to less than the one-sigma level.

#### December, 1986

Figures 4a-f present observations of Venus five weeks past the inferior conjunction of 1986. These observations are unique in that the  $^{13}\text{CO}$  absorption is extraordinarily deep (cf. figures 2c, 3d, 4e, 5d, and 6f) and that a spectrum of  $\text{C}^{18}\text{O}$  was measured (figure 4f). As discussed above, the fits to the  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  observations are consis-

tent with a terrestrial ratio for  $^{13}\text{CO}/\text{C}^{18}\text{O}$  (i.e.,  $5.8 \pm 0.8$ ). The temperature profile derived from the 1986 CO spectra, as indicated in figures 7a and 7b, is 15-20 K warmer than the Pioneer-Venus profile over the 85-100 km altitude range. Synthetic spectra of the 1.3 mm transition of  $^{12}\text{CO}$  corresponding to a Pioneer-Venus temperature profile are provided in figures 4a and 4b as solid lines.

CO mixing profiles derived from the 1986 observations are presented in figure 8c. Notice that the nighttime variation of CO is enhanced by greater than a factor-of-ten relative to the other periods of observations. It was also necessary to extend the nighttime diurnal variation to altitudes below 90 km. The local time for the center of this CO "bulge" is assumed to be 3 AM, so that it lies close to the center of the visible disk of Venus. The extreme nighttime CO "bulge" implied by the CO mixing profiles of figure 8c is required to fit the absorption depths of the moderate opacity 2.6 mm  $^{12}\text{CO}$  spectra (figures 4c and 4d) simultaneously with the absorption depths of the low opacity  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  spectra (figures 4e and 4f). In order to synthesize very deep  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  absorptions and maintain moderate depth 2.6 mm  $^{12}\text{CO}$  absorptions, it is necessary to concentrate CO mixing abundances within a smaller region on the nighttime disk of Venus. The low-opacity  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  absorptions scale linearly with the total nighttime CO abundance, even when it is concentrated within a narrow region of the nighttime disk. The 2.6 mm  $^{12}\text{CO}$  line becomes optically thick when the CO mixing ratios increase by a factor-of-two above the nominal nighttime values. Consequently, the region of very high CO abundances within the CO "bulge" does not lead to substantially increased 2.6 mm  $^{12}\text{CO}$  line absorptions. In this manner it is possible to synthesize very deep  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  line absorptions while maintaining modest 2.6 mm  $^{12}\text{CO}$  absorption depths.

We show the expected 2.6 mm  $^{12}\text{CO}$  absorption for a nominal nighttime distribution of CO in figures 4c and 4d (solid lines), where we have derived CO mixing profiles with a diurnal variation similar to that of figure 8a to fit the  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  spectra ob-



served in 1986. Although the spectral baselines of the 1986 2.6 mm spectra are degraded by standing waves, it is clear that synthetic spectra corresponding to nominal nighttime CO distributions seriously overestimate the 2.6 mm line center absorption. It is difficult to assess the uniqueness of the solution for an extreme CO "bulge" from our 1986 observations. However, in discussion following this presentation of results we address corroborative observations of this unusual 1986 CO "bulge."

#### May, 1988

Observations of Venus three weeks prior to the inferior conjunction of 1988 are presented in figures 5a-e. These observations include a broadband (512 MHz) 1.3 mm  $^{12}\text{CO}$  spectrum (figure 5c) which allows a modest improvement in the minimum altitude to which information on the CO mixing profile is available. The temperature profile derived for 1988 period (figures 7a and 7b) is 5-15 K warmer than the Pioneer-Venus profile, which is comparable to the relative uncertainty of the temperature measurement. The fitted 1.3 mm  $^{12}\text{CO}$  spectra for a Pioneer-Venus temperature profile (figures 5a and 5b) are only 2-3 % deeper than the observed and best fit spectra.

The CO mixing profiles derived from the 1988 observations are presented in figure 8d. Analysis of the 2.6 mm  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra does not suggest the presence of the extreme CO "bulge" in 1988, although the sub-Earth local time on Venus was 6 hours earlier relative to that for the 1986 observations.

#### February, 1990

The 1990 observations were taken roughly 3 weeks after inferior conjunction and coincided to the day with the Galileo flyby of Venus. The mesospheric temperature profile found for the 1990 period (figures 7a and 7b) was found to be completely consistent with the Pioneer-Venus profile, although the detailed shape of the profile, such

as the temperature inversion between 90 and 100 km, is not determined by the microwave observations.

The 1990 nighttime distribution of CO above 90 km altitude does not exhibit the extreme CO "bulge" as observed in 1986, even though the local times of the sub-Earth point were similar for these two periods. However, the 1990 observations present the broadest 1.3 mm  $^{12}\text{CO}$  absorption lines of all of the periods observed. Hence, the CO mixing ratio derived for the 80 km altitude level (corresponding to the 1.3 mm  $^{12}\text{CO}$  absorption at 10 MHz from line center, see figure 1) is greater than four times the abundance inferred in 1985. Differences among the 1982-1990 derivations of CO mixing ratios in the 80-90 km altitude range are significantly above the 30% uncertainties in these measurements. Temporal variations observed for the mesospheric CO abundances are presented in the discussion section.

## DISCUSSION

Our analysis of microwave observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  indicate significant global changes in the thermal and compositional structure of the Venus mesosphere over the 1982-1990 period. Most of these changes are temporally related to one another in that they appear rather dramatically in 1985-1986. On the other hand, observations in 1982, 1988, and 1990 indicate nighttime temperatures and CO distributions comparable to those observed during 1978-1980, by Pioneer-Venus and ground-based measurements. In the discussion below we address independent measurements of the Venus mesosphere which bear upon the changes we have inferred from our microwave observations, and assess the implications of these changes.

### 1985-1986 Changes in Mesospheric Temperatures

We find that low-to-mid latitude atmospheric temperatures in the 85-100 km altitude range were 30-40 K warmer in early 1985 than indicated by Pioneer-Venus observations in 1978-1979. By late 1986, we observed mesospheric temperatures which were still 15-20 K above the Pioneer-Venus temperatures. The elevated temperatures observed in 1985 and 1986 are 2-4 standard deviations in measurement error above the Pioneer-Venus temperature profile for low-to-mid latitudes. In contrast, we observed mesospheric temperatures in early 1982, mid-1988, and early 1990, which are quite consistent with the Pioneer-Venus measurements.

There are few observations of Venus atmospheric temperatures which overlap in altitude and time with our microwave determinations. We have used the Pioneer-Venus primary mission (1979) observations as a standard of comparison. Additional measurements of the mesospheric temperature profile have been returned by the accelerometer measurements from Venera probes in 1975, 1978, and 1983; and from continued radio occultation observations by the Pioneer-Venus orbiter. The mesospheric temperature profiles returned by Veneras 11 and 12 in 1978 are consistent with Pioneer-Venus observations roughly one year later (Arduevsky et al., 1983). Infrared sounding observations by Venera 15 in late 1983 also indicate mesospheric temperatures similar to those observed by Pioneer-Venus (Spätkuch et al., 1989). The mesospheric temperature profile inferred from the deceleration of the Venera 10 entry probe in 1975 is, however, distinctly warmer than the Pioneer-Venus standard profile by 20-30 K over the 75 to 95 km altitude range (e.g., Arduevsky et al., 1983). We have reproduced the Venera 10 mesospheric temperature profile for comparison with the microwave and Pioneer-Venus profiles in figure 7. The Venera 10 profile, taken at face value, appears to suggest that the warmer low-to-mid latitude temperatures we observed in 1985-1986 were also present in late 1975.

A contemporaneous comparison with our microwave observations is provided by radio occultation observations from Pioneer-Venus over the 1978-1987 period. Such observations return the 60-90 km profile of atmospheric temperature as a function of latitude and local time on Venus (Kilore and Patel, 1980). The polar orbit of the Pioneer-Venus orbiter leads to better observational coverage at high latitudes and much-reduced coverage for latitudes below 45 degrees. In figures 9 a-d we show the 1978-1987 time dependence of Venus temperatures at altitudes of 60, 70, 80, and 90 km for latitude bins of 75-90N, 20-45N, 20-45S, and 45-60S, (from Kilore and Mullen, 1988). The equatorial region is not shown since observations for this region were not available after late 1983. The error bars indicate the standard deviations for the distribution of observed temperatures at each altitude, latitude, and period.

Although the observed variations are quite large at 80 and 90 km, figures 9 b and c suggest that atmospheric temperatures at 80-90 km altitude were warmer in late 1984 for latitudes below 45 degrees. This provides modest support for the warm mesospheric temperatures we observed in early 1985 and late 1986. A better determined result from the Pioneer-Venus radio occultations between 1978 and 1987 is that high latitude temperatures over the 60-80 km altitude range were distinctly cooler in late 1984, for both the north and south hemispheres (see figures 9a and d). Kilore and Mullen (1988) found that high latitude (latitude > 60 degrees) temperatures were an average of 10 K cooler over the 1984-1986 period relative to the 1979-1981 period. Such a difference is large enough to reverse the latitudinal pressure gradient within the mesosphere of Venus. In figure 10, we show the effect on the latitudinal gradient of atmospheric pressure due to 10 K cooler temperatures for high-latitudes over the 60-90 km altitude range. Altitude profiles of the ratio of atmospheric pressures at 0-30 and 75-90 degrees latitudes are presented for the Pioneer-Venus 1979 CIRIA model (long dashed) and for the case of the cooler polar atmosphere observed by radio occultations in late 1984 (solid and dotted).

As was noted by Taylor et al. (1980), the Pioneer Venus OIR observations of the latitudinal pressure gradient in 1979 indicated that the mesosphere of Venus departed from cyclostrophic balance above an altitude of 80 km. As a result, the latitudinal pressure gradient was not in dynamical balance with retrograde zonal flow above an altitude of 80 km. The dynamical implications for the breakdown in cyclostrophic balance within the Venus mesosphere remain controversial, but it is clear that global circulation within the mesosphere is strongly tied to the latitudinal pressure gradient. The cooler polar temperatures observed by Pioneer-Venus radio occultations in late 1984 lead to cyclostrophic balance throughout the mesosphere. In fact the contrast in the latitudinal pressure gradient between 1979 and 1984 is presumably much greater than that shown in figure 10, since we assumed no change in the low latitude temperature profile for the 1984 period. If we include the increased temperatures at low latitudes as inferred from our early 1985 microwave observations (and suggested by the late 1984 radio occultations), the ratio of low-to-high latitude atmospheric pressure increases to 1.9 at an altitude of 80 km for the late 1984- early 1985 period.

#### An Extreme Nightside CO "Bulge" in 1988

We have inferred the presence of an extreme nightside concentration of CO at altitudes of 90-100 km from our December, 1986 observations. The concentration of CO is found to increase by 1-2 orders of magnitude over a narrow solar-zenith-angle (~45 degrees) region in the nightside Venus mesosphere, near a local time of ~3 AM. The local time and angular extent of this extreme CO "bulge" are not well defined by our single dish measurements, since we do not spatially resolve the disk of Venus. However, Muhleman et al. (1988) observed the 2.6 mm <sup>12</sup>CO spectrum of Venus with the Owens Valley millimeter array just two weeks prior to our December, 1986 observations. Muhleman et al. were able to construct maps of CO spectral lines with roughly 10 elements of resolution across the nightside disk of Venus. The presence of an ex-

treme CO "bulge" at ~3 AM local time is clearly visible in their interferometric map of <sup>12</sup>CO spectra. Preliminary modelling of the CO mixing profiles indicates 1-2 order of magnitude variations in the CO mixing ratio at 90-100 km across the nightside disk of Venus (Muhleman et al., 1988). We point out that this extreme CO "bulge" is significantly shifted in local time relative to the 12 AM location of the much smaller CO "bulge" observed over the 1978-1982 period from ground-based observations of the phase dependence of <sup>12</sup>CO microwave line depths (Clancy and Muhleman, 1985a). The 12 AM location was interpreted as an indicator of very weak zonal winds at the 100 km altitude level. Hence, the 3 AM location of the extreme CO "bulge" observed in late 1986 may indicate increased zonal winds at 100 km in 1988.

We also note that interferometric mapping of 2.6 mm <sup>12</sup>CO spectra was repeated by Pierce et al. (1989) in 1988, with improved signal-to-noise ratios in order to derive mesospheric wind velocities from doppler shifts of the CO lines. These observations were at a distinctly different sub-Earth local time on Venus as compared to the 1986 observations (8 PM vs 2 AM). Pierce et al. found no indication of the extreme CO "bulge" observed by Muhleman et al. in 1988.

#### Interannual Variations in Mesospheric CO Abundances

The individual CO mixing profiles derived from 1982, 1985, 1986, 1988, and 1990 microwave spectra of CO indicate significant interannual variations in mesospheric CO abundances (figures 8a-e). In figure 11a we plot the observed time dependence of the column of CO above a pressure level of 1 mbar (~88 km altitude). This column is calculated as the whole-disk average CO column appropriate to the sub-Earth local time at each observational period. The variable local time of the sub-Earth point among the observations and the assumed diurnal variation in CO mixing above an altitude of ~90 km would lead to an observed variation in the CO column above 1 mbar, even in the absence of any interannual variation in mesospheric CO mixing

ratios. We model this "local time" effect in the observed CO column, which is presented by the solid line and crosses in figure 11a. The observed variations in the CO column abundance above 1 mbar (dashed line and boxes) are considerably in excess of this observational effect.

Figure 11b presents the interannual variation observed for CO mixing ratios at an altitude of 80 km. Similar variations are observed for CO mixing ratios to as low as 75 km altitude. However, the experimental uncertainties in CO mixing ratios increase from 30 % to >50 % between an altitude of 80 and 75 km. The CO mixing ratio exhibits a factor-of-four increase between 1985 and 1986, at the 80 km level. This change is comparable to the increase in the CO column above ~86 km altitude, which occurred between 1982 and 1985 (figure 11a). Although comparative measurements of changes in other mesospheric species are not available, we point out a similarity to SO<sub>2</sub> variations observed near the cloud top region by Esposito et al (1988). Esposito et al. report greater than a factor-of-four decrease in the global SO<sub>2</sub> abundance at 65-70 km in early 1979. Both the SO<sub>2</sub> and CO mixing profiles exhibit steep vertical gradients within the Venus mesosphere. We suggest that interannual variations in the circulation of the Venus mesosphere may lead to interannual variations in the mesospheric abundances of SO<sub>2</sub> and CO, and that the timing of these variations may be highly altitude-dependent.

## Summary

We have observed global-scale changes in both the chemistry and thermal structure of the Venus atmosphere over the 75-105 km altitude range. The changes we infer from microwave observations of mesospheric <sup>12</sup>CO and <sup>13</sup>CO were most dramatic in 1985-1986, when atmospheric temperatures at 85-100 km were elevated by 20-40 K at low-to-mid latitudes, relative to the 1979 period observed by Pioneer-Venus. A similar increase in mesospheric temperatures was observed in 1975 by Venera 10

probe deceleration observations (Arduevskiy et al., 1983). Examination of Pioneer-Venus radio occultation measurements of atmospheric temperature over the 1978-1987 period indicates that high latitude temperatures between 60 and 90 km altitude were ~10 K cooler during late 1984 (Kilore and Mullen, 1988). We show that the latitudinal gradient of atmospheric pressure within the Venus mesosphere in late 1984 is consistent with cyclostatic balance throughout the entire mesosphere of Venus. This is in contrast to the breakdown of cyclostatic balance above an altitude of 80 km, as observed by Pioneer-Venus in 1979 (Taylor et al., 1980).

We also infer global changes in the nighttime abundance and distribution of mesospheric CO between 1982 and 1990. The largest changes are observed to occur in 1985-1986. The column of CO above the 1 mbar pressure level (or ~86 km altitude level) increased by a factor-of-four between our 1982 and 1985 observations. The CO mixing ratio at 80 km presents a factor-of-four increase between our 1985 and 1986 microwave observations. Furthermore, an extreme nighttime CO "bulge" is inferred from our 1986 microwave spectra. At altitudes above 85 km, the CO mixing ratio exhibited 1-2 orders of magnitude variation in solar-zenith-angle, leading to very high CO abundances concentrated in a narrow region on the nightside of Venus. The local time (3 AM) and nighttime gradient of this CO "bulge" are more directly determined from 2.6 mm interferometric observations of CO in 1986 (Mulleman et al., 1988).

We speculate that the global changes in the mesosphere of Venus we observed in 1985-1986 may reoccur on a poorly constrained timescale of ~10 years, based on the 1975 Venera 10 observations and on the 5-10 year cyclic variability of cloud top dynamics observed by Del Genio and Rossow (1989). Changes in the thermal structure and the latitudinal pressure gradient of the mesosphere suggest that the gross circulation of the mesosphere is perturbed during such times, from the state observed by Pioneer-Venus measurements in 1979. Large variations in the vertical and solar-zenith-angle distribution of mesospheric CO appear to be driven by these

perturbations to the dynamical state of the Venus mesosphere. We also suggest that the global decay in cloud top level  $\text{SO}_2$  observed by Esposito et al. (1988) in 1979 is related to changes in the dynamics of the Venus mesosphere, rather than sporadic volcanism.

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#### FIGURE CAPTIONS

Figure 1. Atmospheric temperature weighting functions provided by microwave line opacities of  $^{12}\text{CO}$  (short dashed) and  $^{13}\text{CO}$  (long dashed) are shown for an air mass ( $1/\mu$ ) of two in the Venus mesosphere. Four separate weighting functions are provided for the  $1.3\text{mm}$   $^{12}\text{CO}$  line at various frequency offsets,  $\nu-\nu_0$ , from line center. The  $1.2\text{mm}$   $^{13}\text{CO}$  line center weighting function has been scaled by a factor-of-five to enhance its visibility in this presentation. The low-to-mid latitude mesospheric temperature profile of Venus as determined by Pioneer Venus observations in 1979, is indicated by the solid line.

Figure 2. Microwave spectral line observations of the whole disk of Venus near inferior conjunction in 1982 are presented. The observed spectra are indicated by solid "barred" lines, the best fit synthetic lines are given by the smooth dashed lines. The temperature and CO mixing profiles used to generate these synthetic spectra are presented in figures 7 and 8. The dates of observations, the sub-Earth local time on Venus, and the percentage of the visible disk corresponding to nighttime on Venus are also provided for each observation. a) a  $250\text{ KHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$ . b) a  $1\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$ . c) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $^{13}\text{CO}$ .

Figure 3. Microwave spectral line observations of the whole disk of Venus near inferior conjunction in 1985 are presented. Explanation of various lines shown follow that described in figure 2, with the addition of best fit synthetic spectra [solid smooth lines in a) and b)] corresponding to a 1979 Pioneer Venus mesospheric temperature profile. The 1985 observations include a) a  $250\text{ KHz}$   $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  b) a  $1\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  c) a  $100\text{ KHz}$  resolution  $2.6\text{mm}$  spectrum of  $^{12}\text{CO}$  d) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $^{13}\text{CO}$ .

Figure 4. Microwave spectral line observations of the whole disk of Venus near inferior conjunction in 1986 are presented. The figure description follows that presented for figures 2 and 3. The 1986 observations include a) a  $250\text{ KHz}$  resolution

$1.3\text{mm}$  spectrum of  $^{12}\text{CO}$ . b) a  $1\text{ MHz}$  resolution spectrum of  $^{12}\text{CO}$  c) a  $100\text{ KHz}$  resolution  $2.6\text{mm}$  spectrum of  $^{12}\text{CO}$  d) a  $500\text{ KHz}$  resolution  $2.6\text{mm}$  spectrum of  $^{12}\text{CO}$  e) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $^{13}\text{CO}$  f) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $\text{C}^{18}\text{O}$ . The best fit spectra adopt terrestrial ratios for  $^{12}\text{CO}/^{13}\text{CO}$  and  $^{13}\text{CO}/\text{C}^{18}\text{O}$ .

Figure 5. Microwave spectral line observations of the whole disk of Venus near inferior conjunction in 1988 are presented. The figure description follows that presented for figures 2 and 3. The 1988 observations include a) a  $250\text{ KHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  b) a  $1\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  c) a  $2\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  d) a  $250\text{ KHz}$  resolution  $2.6\text{mm}$  spectrum of  $^{12}\text{CO}$  e) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $^{13}\text{CO}$ .

Figure 6. Microwave spectral line observations of the whole disk of Venus near inferior conjunction in 1990 are presented. The figure description follows that presented for figure 2. The 1990 observations include a) a  $250\text{ KHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  b) a  $1\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  c) a  $2\text{ MHz}$  resolution  $1.3\text{mm}$  spectrum of  $^{12}\text{CO}$  d) a  $250\text{ KHz}$  resolution  $2.6\text{mm}$  spectrum of  $^{12}\text{CO}$  f) a  $100\text{ KHz}$  resolution  $1.2\text{mm}$  spectrum of  $^{13}\text{CO}$ .

Figure 7. Temperature profiles for the Venus mesosphere as derived from the 1982, 1985, 1986, 1988, and 1990 microwave observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$ , are indicated by the various lines. The relative uncertainties among the microwave determinations are given by the horizontal error bars on the 1985 temperature profile. The absolute uncertainty for all of these temperatures is  $\pm 15\text{K}$ . The CIRA reference profile, based on low-to-mid latitude Pioneer Venus measurements in 1979, is provided at  $5\text{ km}$  intervals by the box symbols. The anomalously warm temperatures returned by the Venera 10 probe in 1975 are shown as cross symbols. Temperatures are plotted versus a) altitude and b) atmospheric pressure.

Figure 8. Profiles of the volume mixing ratio of CO within the nightside Venus mesosphere were determined from  $^{12}\text{CO}$  and  $^{13}\text{CO}$  microwave observations; in a) January 1982 b) March 1985 c) December 1986 d) May 1988 and e) February 1990. One-sigma uncertainties are indicated versus altitude-pressure. The multiple profiles of CO mixing above an altitude of 90 km show the diurnal variation in mesosphere CO abundance assumed in the calculations of synthetic  $^{12}\text{CO}$  and  $^{13}\text{CO}$  spectra. Except in 1986, the variation in CO is represented by a solar-zenith-angle symmetric "bulge" of CO centered at the equator with a local time of 12AM. The 6PM, AM to 12AM (and equator-to-pole) variation in CO mixing ratios is roughly a factor-of-two at 95km altitude. In 1986 (c), the CO "bulge" is centered at a local time of 3AM, and the modelled variation in CO mixing ratios at 95 km is roughly a factor-of-ten.

Figure 9. Pioneer Venus radio occultation measurements of temperatures in the Venus atmosphere are shown for altitudes of 60, 70, 80 and 90 km, at various times over the 1978-1987 period. The radio occultation temperatures are binned at latitude intervals of a) 75-90N b) 20-45N c) 20-45S and d) 45-60S. The vertical error bars indicate the one-sigma standard deviations for the distribution of temperatures observed within each latitude bin ( these figures were provided by Arnydas Kliore, 1990).

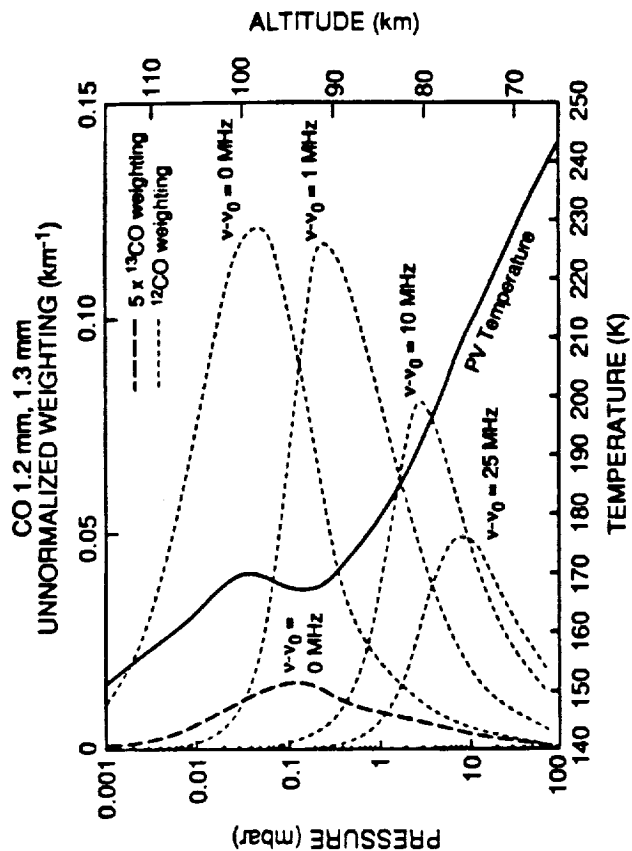
Figure 10. Profiles of the latitudinal gradient of atmospheric pressure within the Venus mesosphere are shown for the 1979 period (long-dashed) and the late 1984 period (solid and dotted). The latitudinal pressure gradient is calculated as the ratio of atmospheric pressures at 0-30 and 75-90 degrees latitude. The 1979 profile is calculated from the CIRA reference atmosphere for Venus. The late 1984 profile assumes 10K decreases in high latitude atmospheric temperatures between 60 and 90km altitude, as indicated by Pioneer Venus radio occultation measurements in late 1984 (Kliore and Mullen, 1988). Low-to-high latitude ratios greater than unity correspond to cyclostrophic balance.

Figure 11. Year-to-year variations in the mesospheric mixing profile of CO are demonstrated from the 1982-1980 microwave observations.

a) the column density of CO above the 1 mbar pressure level (~86km altitude level) is determined for each observational period from the whole-disk-average CO mixing profile. The observed CO columns (boxes with dashed lines) are compared to model calculations (crosses with solid line) which assume a time-invariant CO mixing profile with the altitude and diurnal dependence of the 1988 CO mixing profile (Figure 8d). The 1982-1990 variations in this model CO column result from the variations in sub-Earth local times among the observations.

b) the CO mixing ratio at an altitude of 80km, as inferred from the 1982-1990 microwave observations.



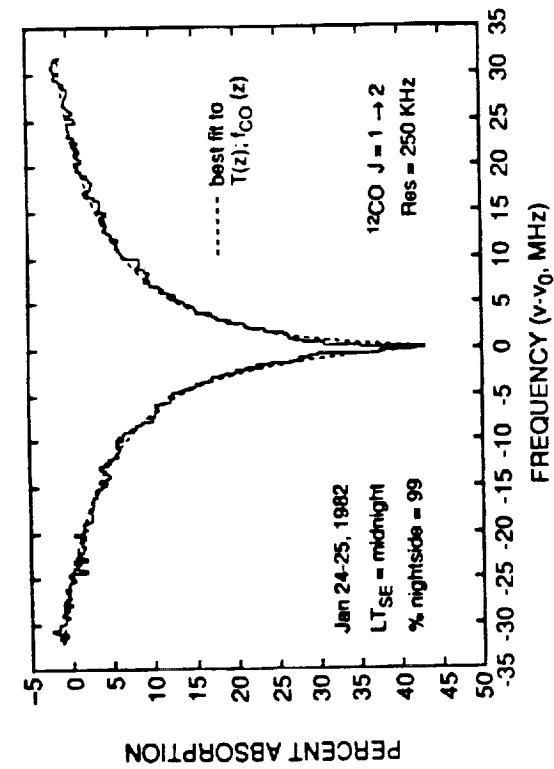


F. 1

Clancy 3-80  
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VEN WFF\*

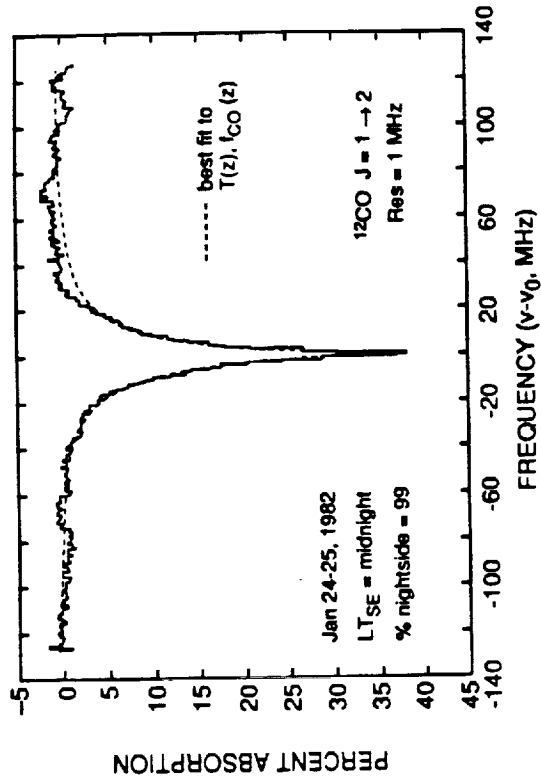
Table 1. A list of observational parameters for 1982-1990 microwave observations of  $^{12}\text{CO}$  and  $^{13}\text{CO}$  in the nightside Venus mesosphere.

Dates of observation	Spectral Lines	Angular Diameter of Venus	Angular Beam of Telescope @ 1.3mm (HWHM)	Fraction of Illumination for Venus	Sub-Earth Local time on Venus
1982 January 24-25	$^{12}\text{CO}$ -1.3mm $^{13}\text{CO}$ -1.2mm	60"	60"	.01	12AM
1985 March 8-9	$^{12}\text{CO}$ -1.3, 2.6 mm $^{13}\text{CO}$ -1.2mm	42"	32"	.19	8:40PM
1986 December 13-16	$^{12}\text{CO}$ -1.3, 2.6 mm $^{13}\text{CO}$ -1.2mm $\text{C}^{18}\text{O}$ -1.2mm	42"	32"	.28	4:20AM
1988 May 14-15	$^{12}\text{CO}$ -1.3, 2.6 mm $^{13}\text{CO}$ -1.2mm	42"	32"	.20	8:30PM
1990 February 9-11	$^{12}\text{CO}$ -1.3, 2.6 mm $^{13}\text{CO}$ -1.2mm	49"	32"	.14	3:00AM



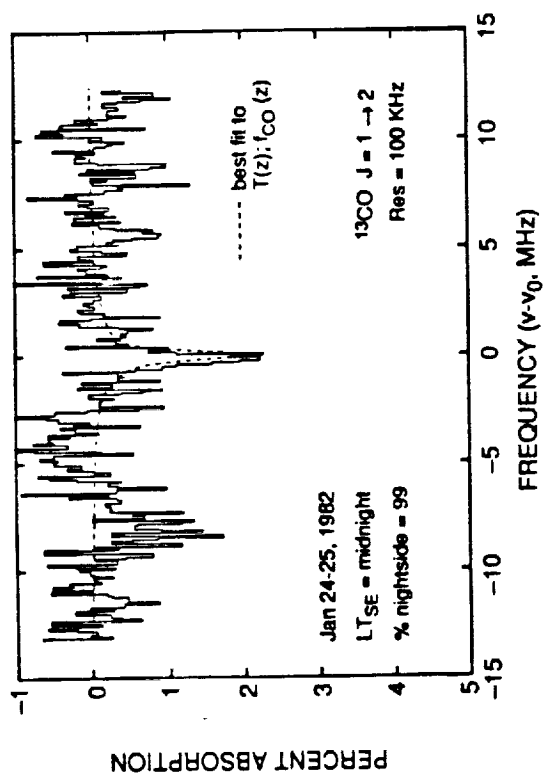
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F2a

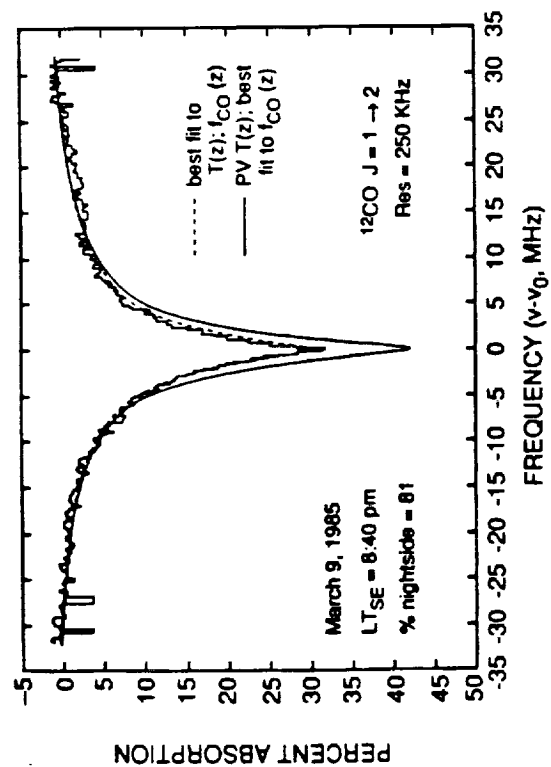


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F2b

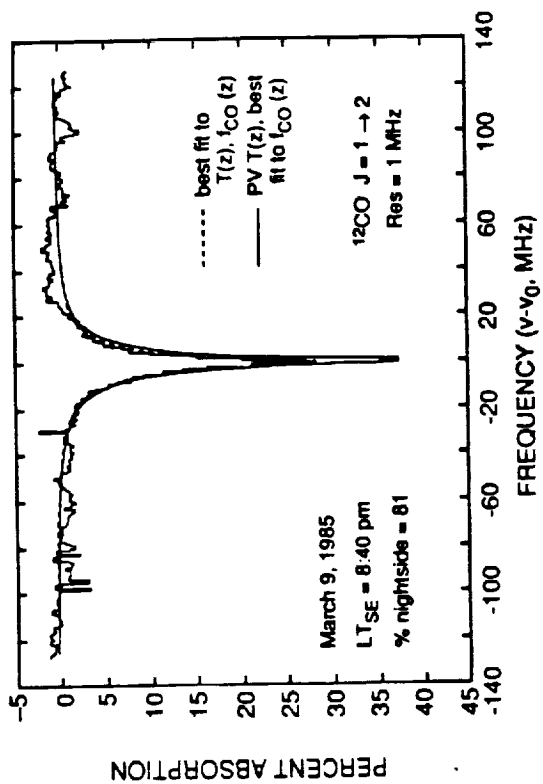


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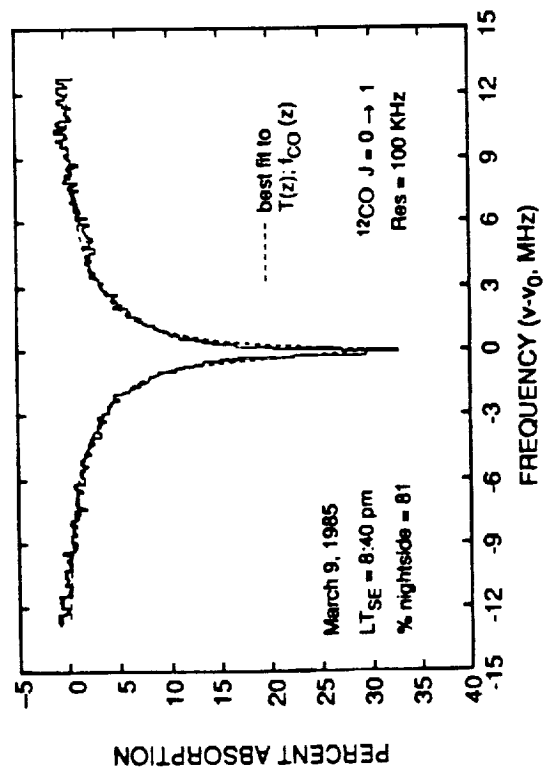
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Clancy: 3-90  
 Venus  
 $^{12}CO$  J2



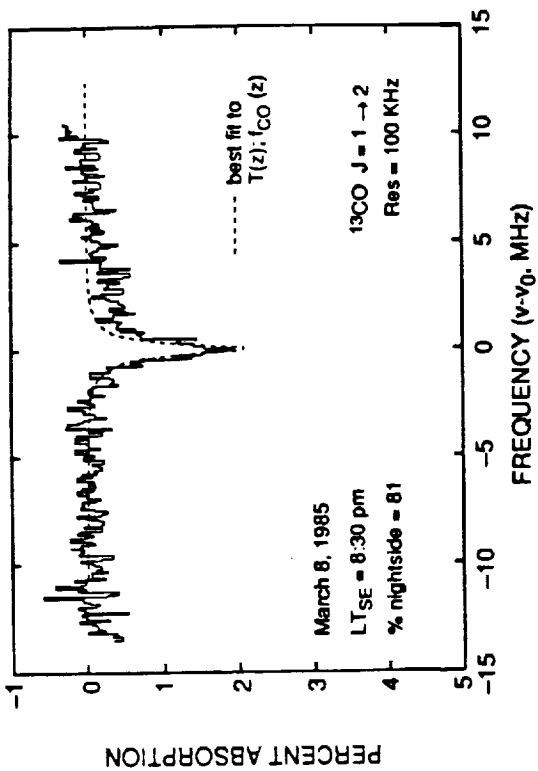
F3b

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 $^{12}CO$  J2 F85



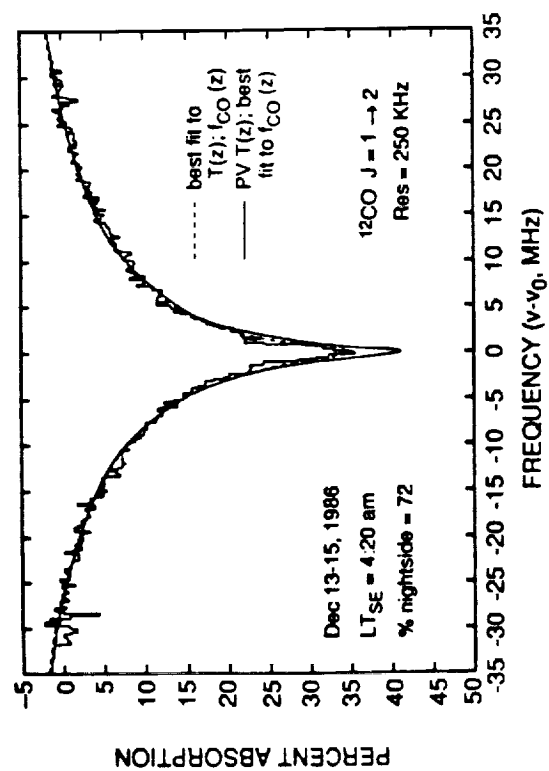
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Clancy 31  
 Venus  
 $^{12}CO\ J = 1$



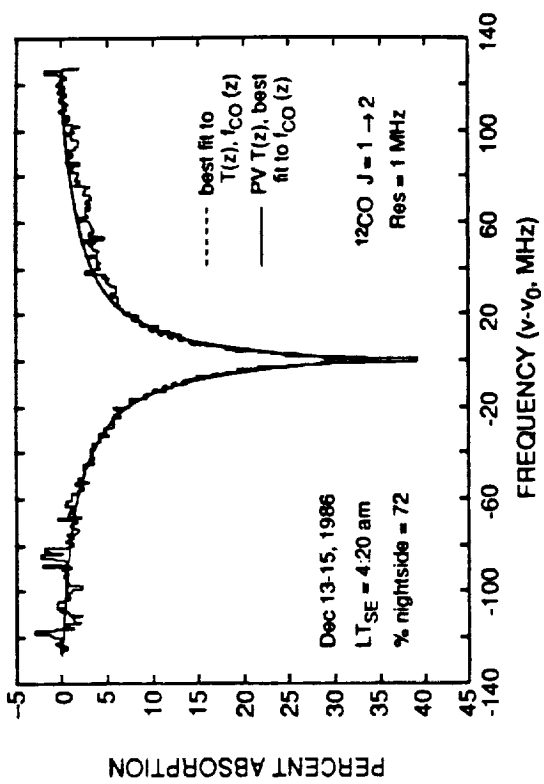
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Clancy 3-80  
 Venus  
 $^{13}CO\ J = 2$



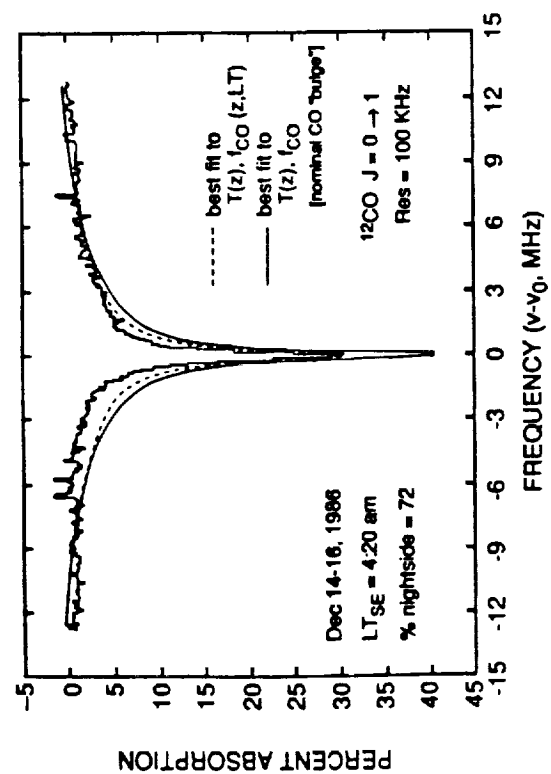
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Clancy 3  
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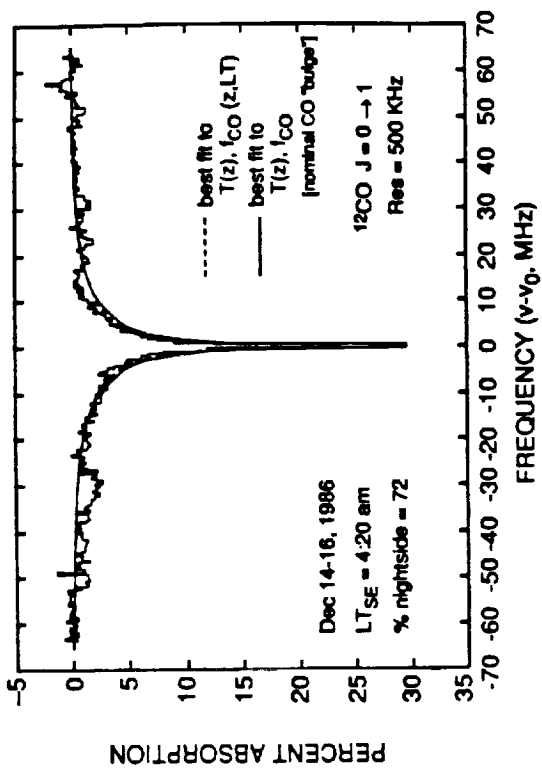


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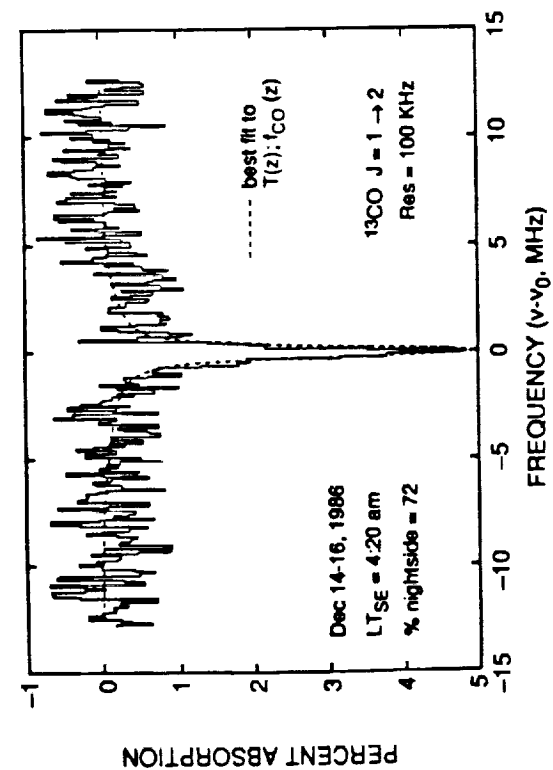
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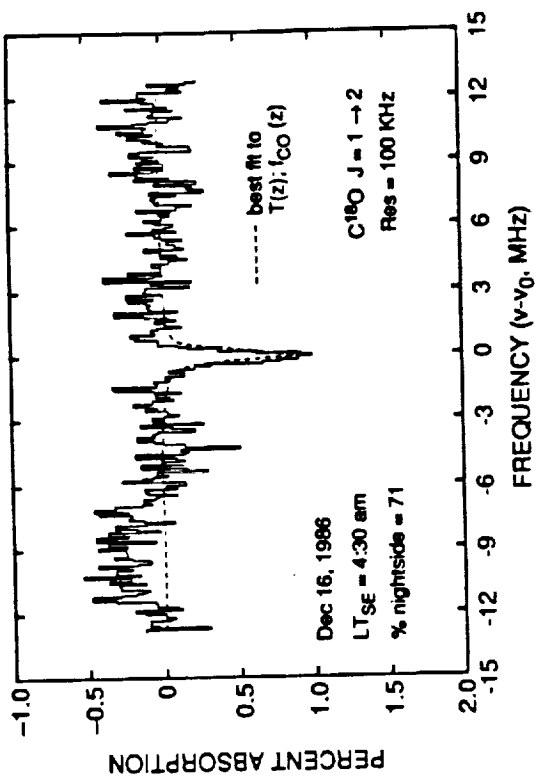
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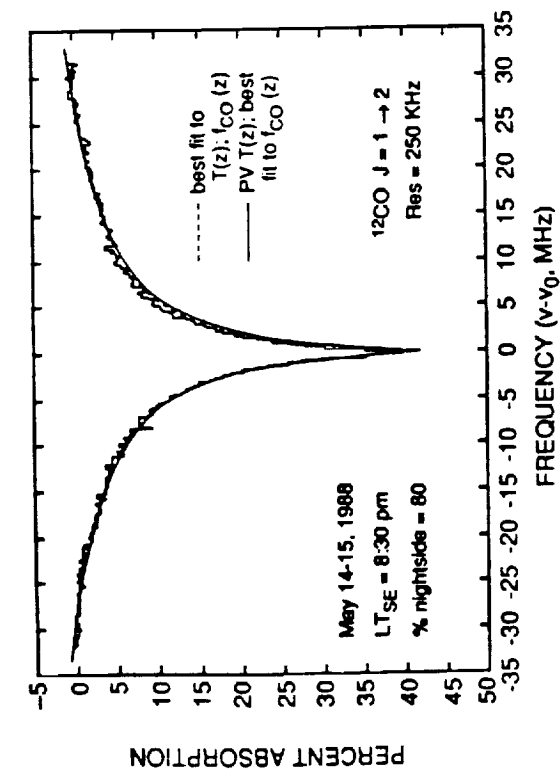
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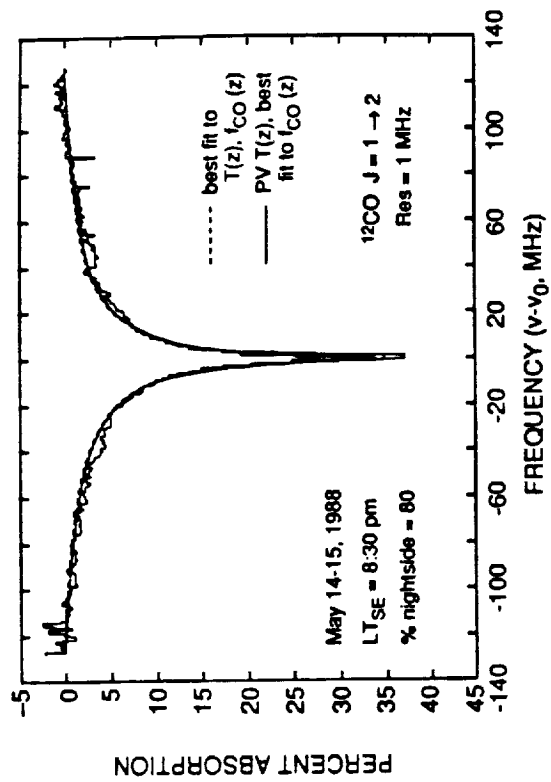
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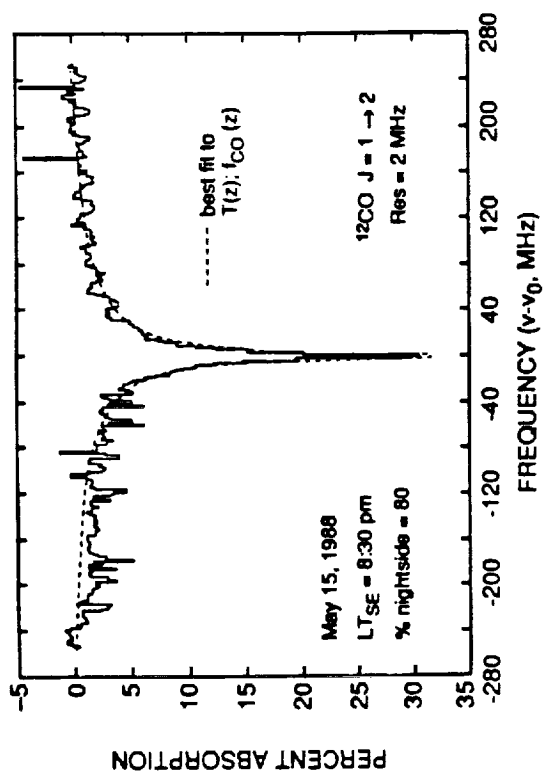
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 Venus  
 $^{12}\text{CO } 12$

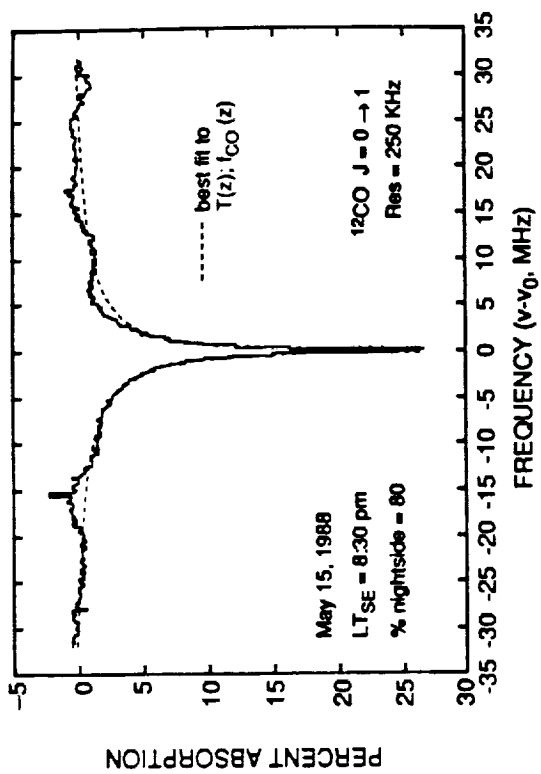


F5b

Clancy 3-80  
 Venus  
 $^{12}\text{CO } 12$



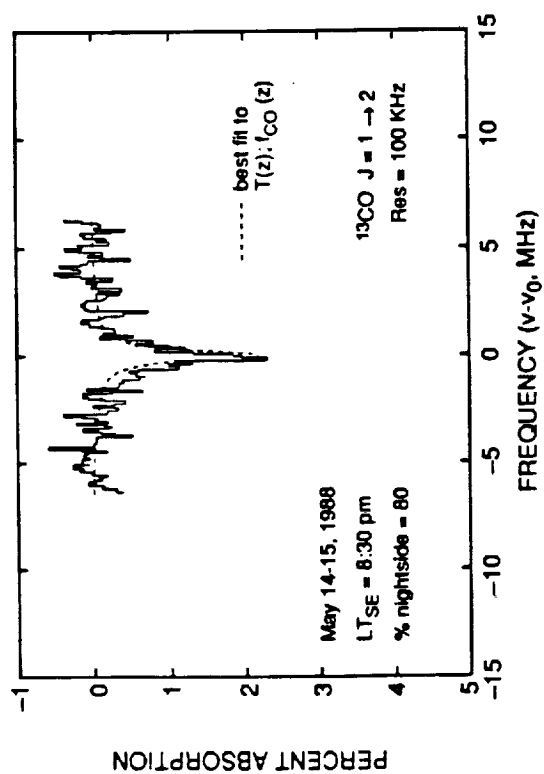
Clancy  
 Venus  
 $^{12}\text{CO } 1$



Clancy 3.80  
 Venus  
 $^{12}\text{CO } 0.007$

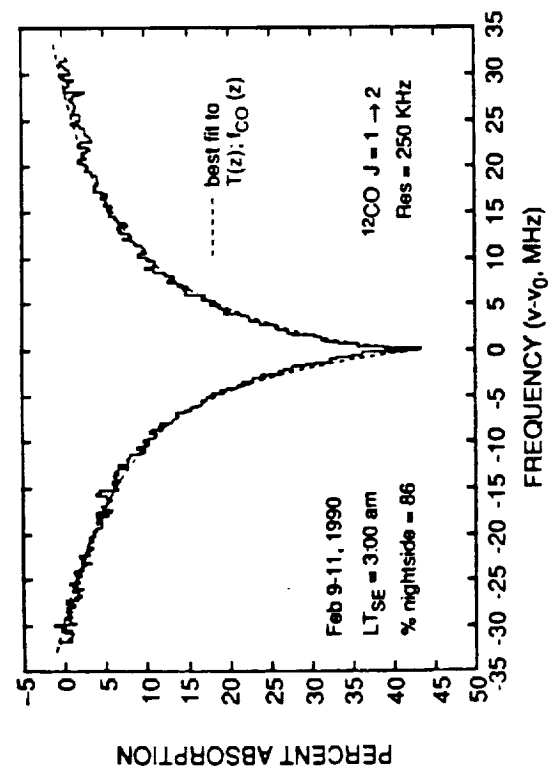
F5c

F5d



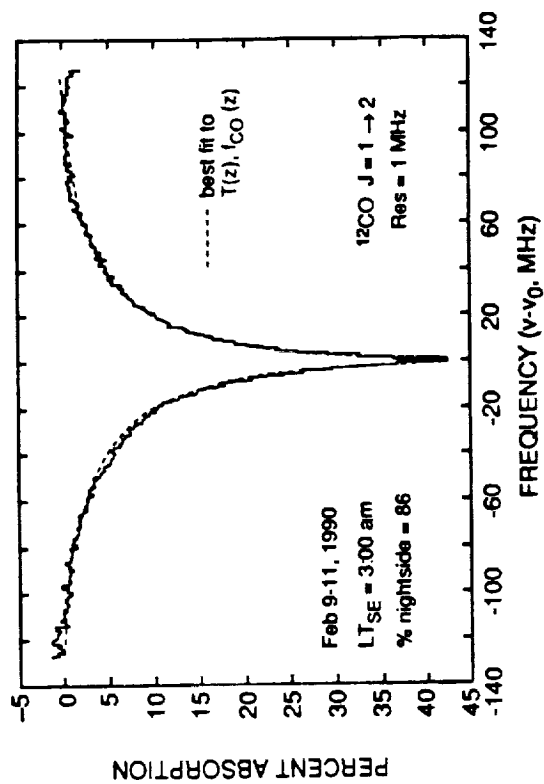
F 5e

Class: 340  
Venus  
"CO 13 T 88"



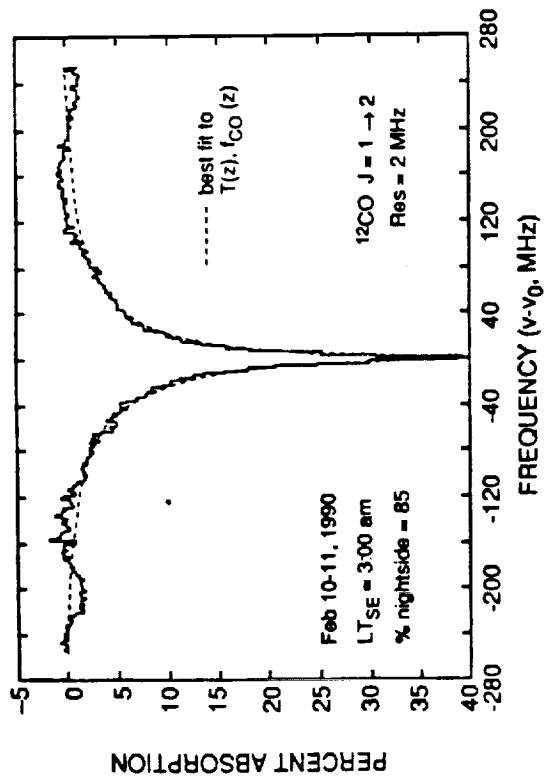
F 6a

Clancy 3  
 Venus  
 -CO 12 C



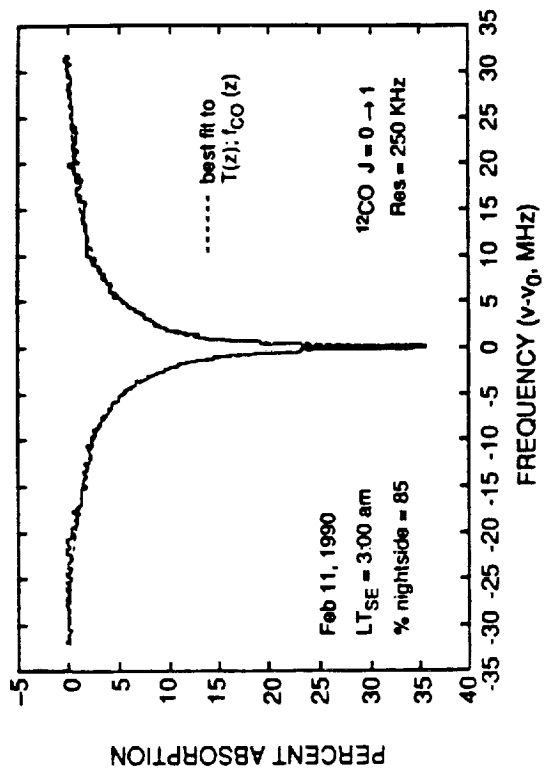
F 6b

Clancy 3-90  
 Venus  
 -CO 12 F 6b



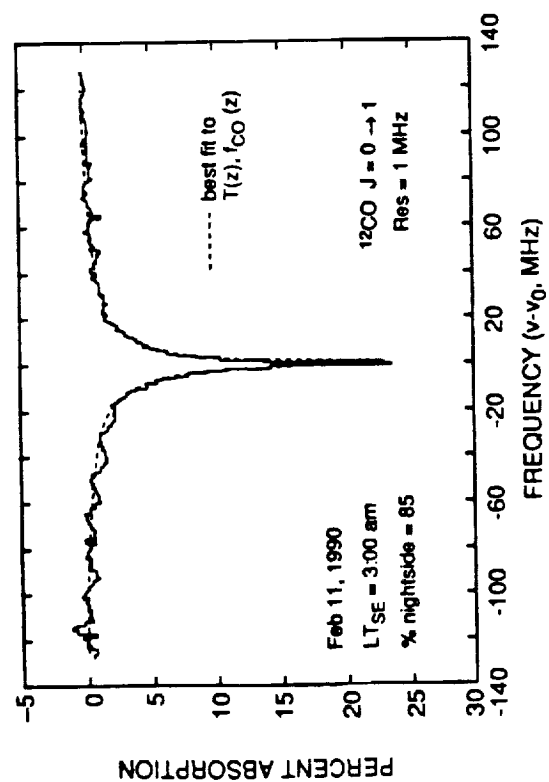
Classy 3  
 Venus  
 CO 12 I

F 6a



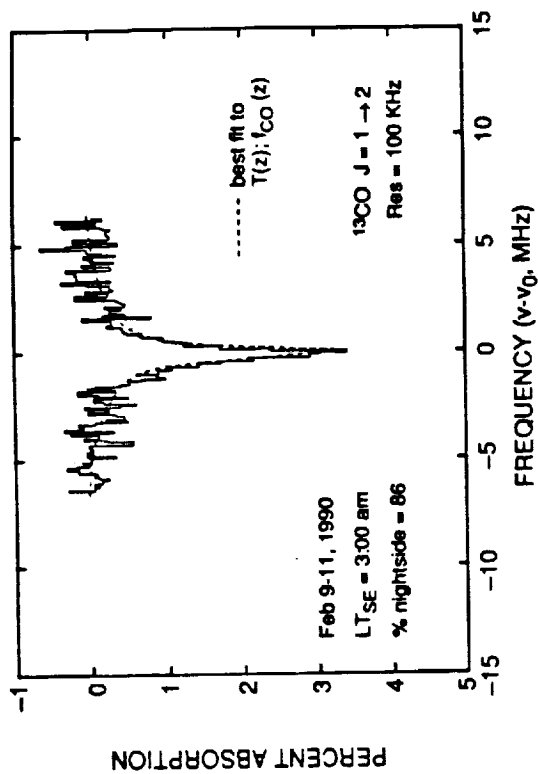
Classy 3 90  
 Venus  
 CO 01 Q 907

F 6d



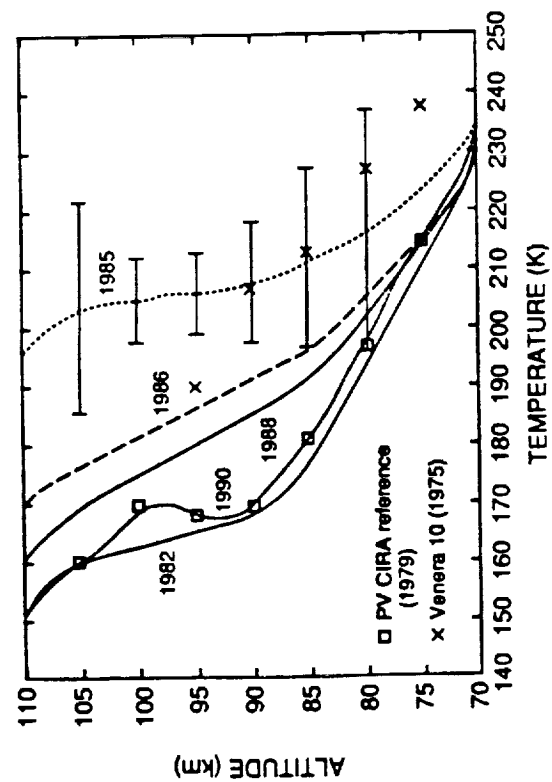
F 6e

Cherry 3 90  
 Venus  
 $^{12}\text{CO } J=0 \rightarrow 1$



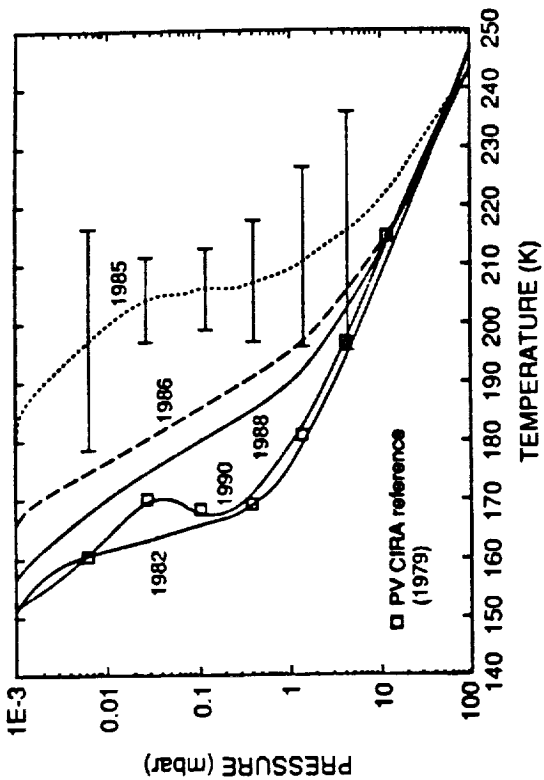
F 6f

Cherry 3 90  
 Venus  
 $^{13}\text{CO } J=1 \rightarrow 2$



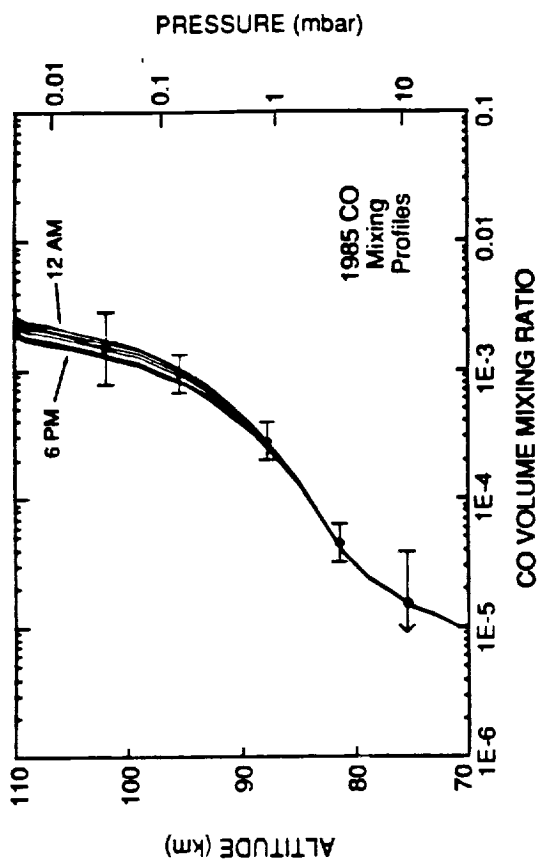
F 7a

Clancy 3-80  
Venus  
"Temp vs Alt"



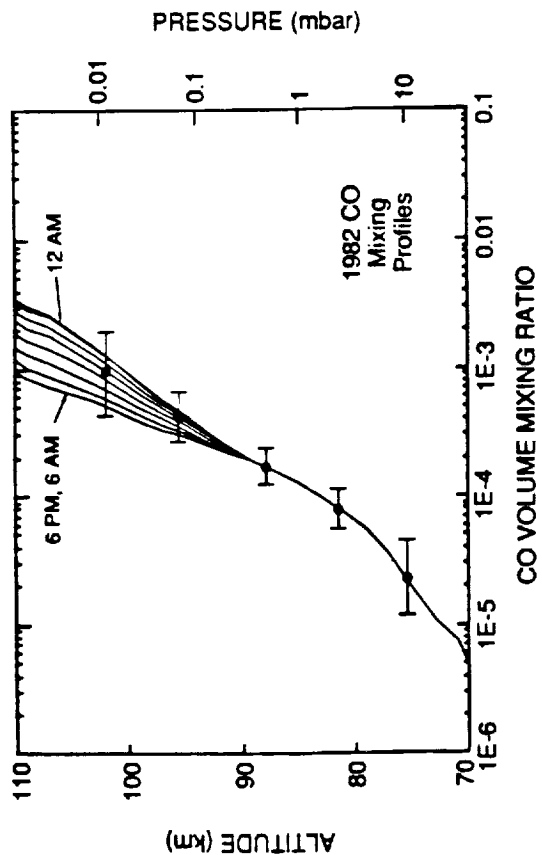
F 7b

Clancy 3-80  
Venus  
"Temp vs Pressure"



F 8b

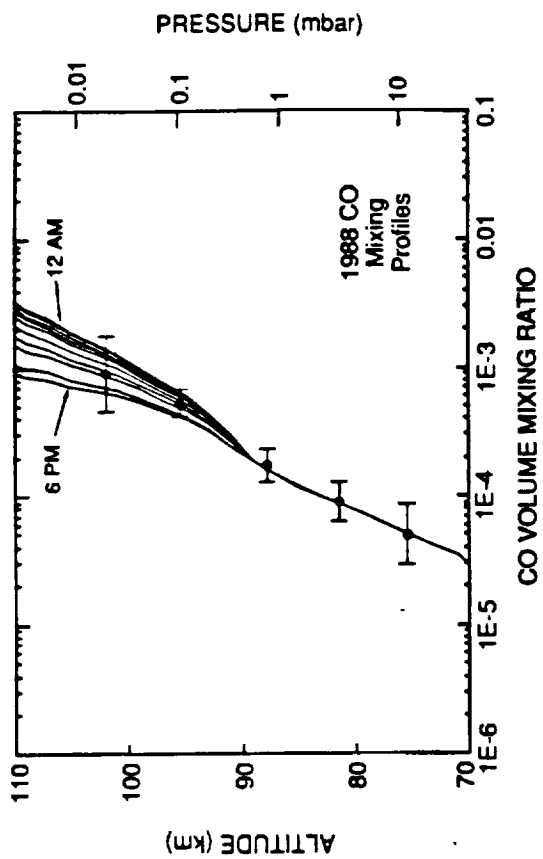
Clancy 3-80  
Venus  
-15 MK



F 8a

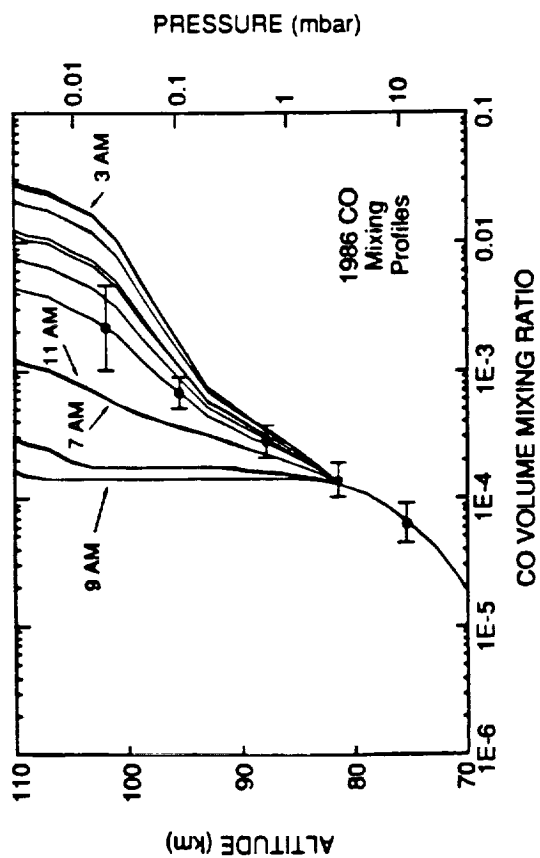
Clancy 3-80  
Venus  
-12 MK





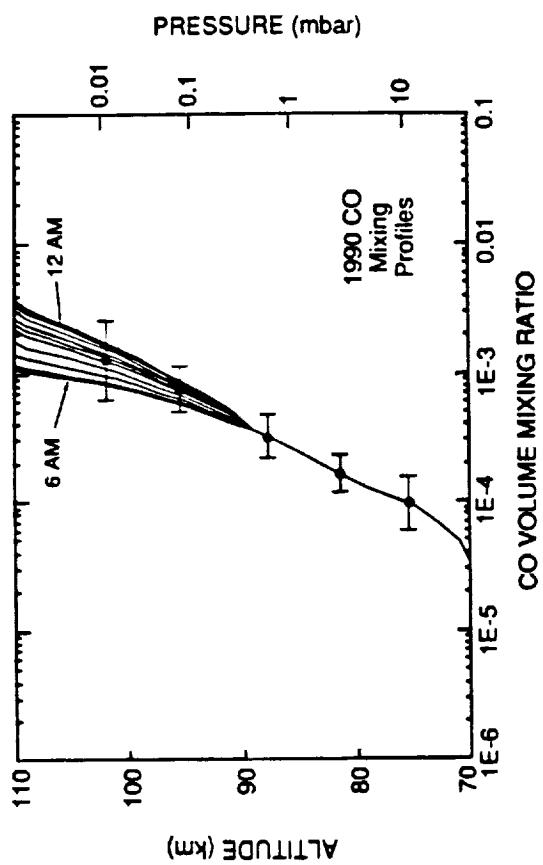
F 8d

Clancy 3-80  
Venus  
780 MEX

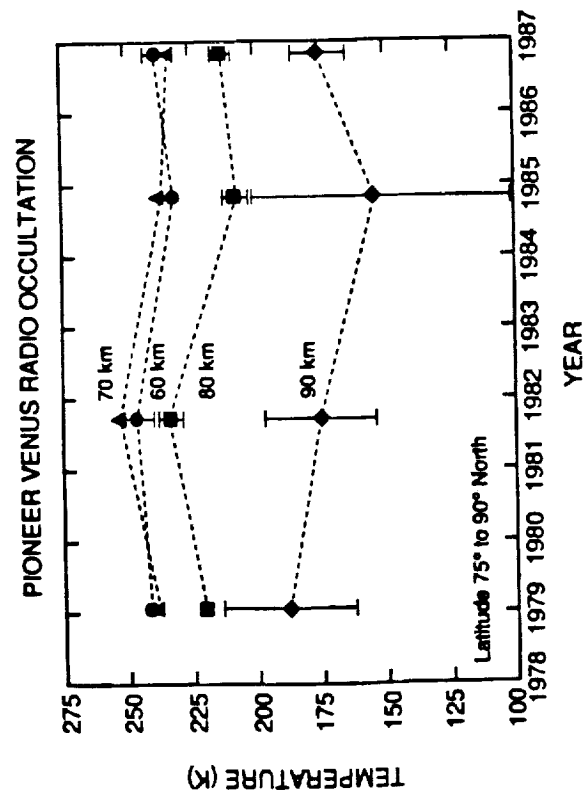


F 8c

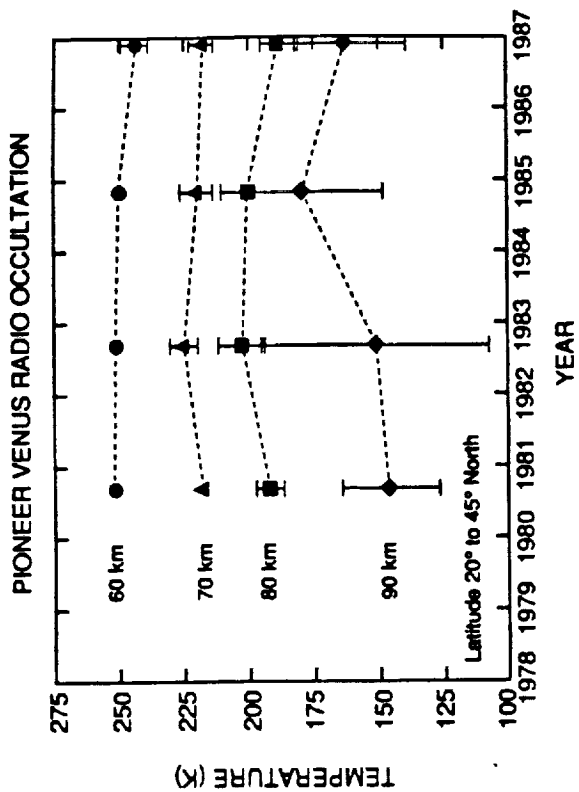
Clancy 3-80  
Venus  
796 MEX



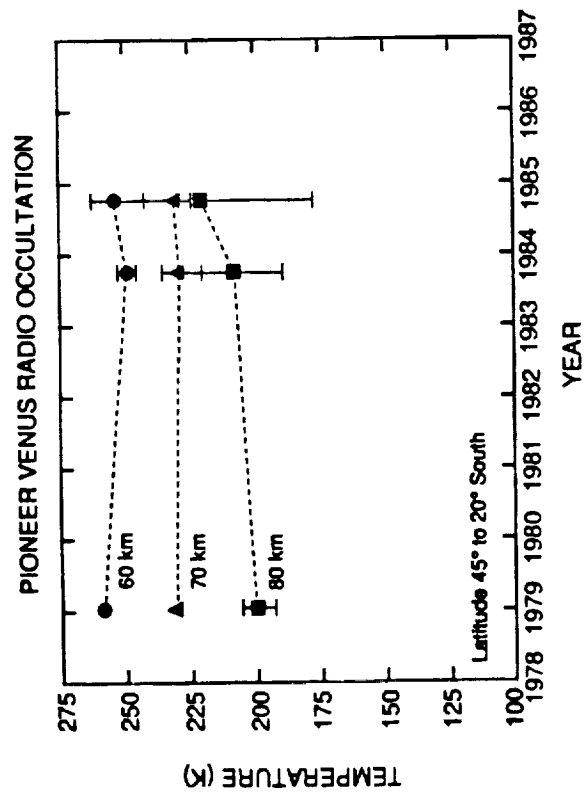
F 8 e



F9a

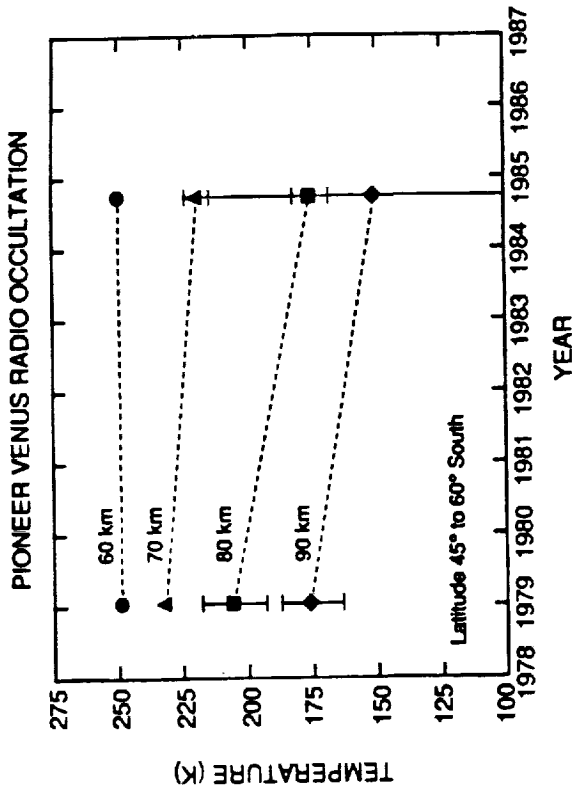


F9b



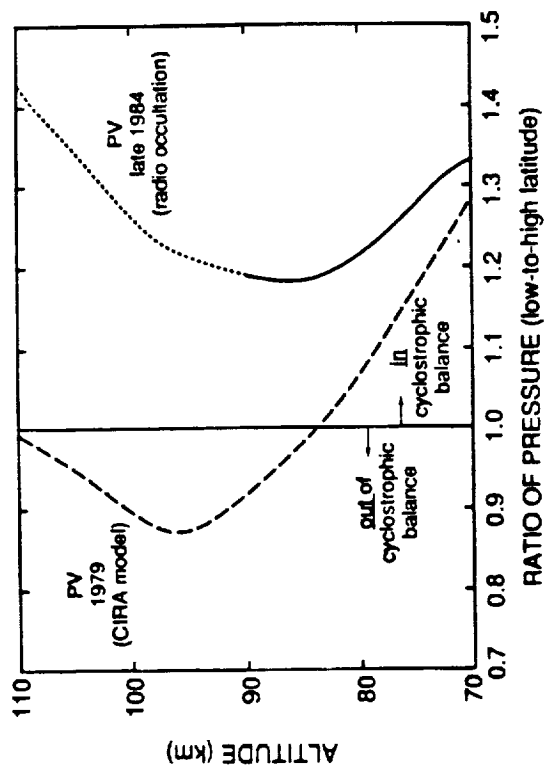
F9c

Clancy 3 80  
Venus  
Radio 45-60°

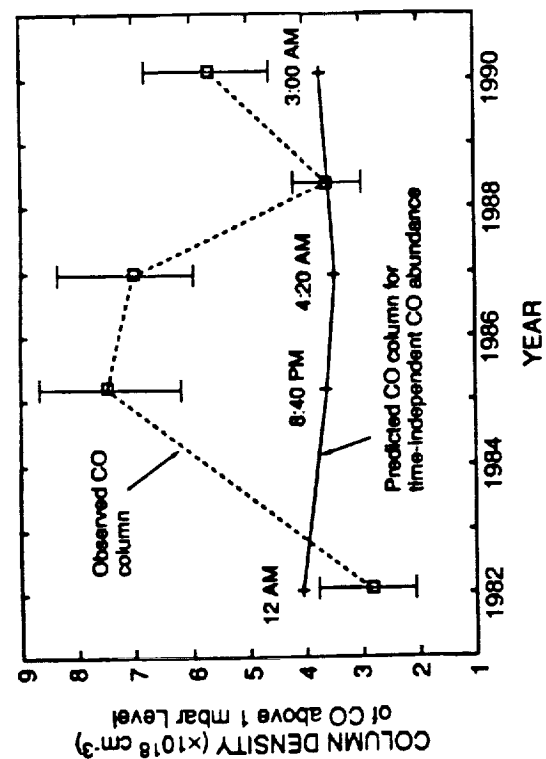


F9d

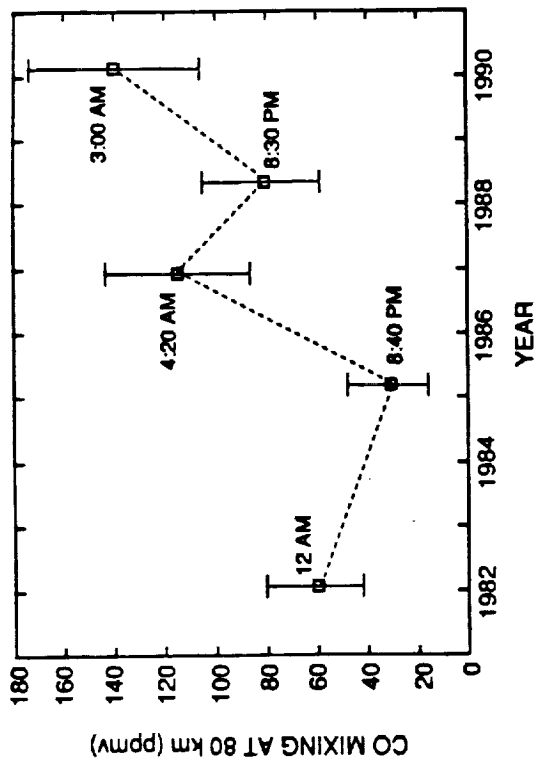
Clancy 3 80  
Venus  
Radio 45-60°



F 10



F11a



F11b

Client:  
Vendor:  
C.O.C.

Client: 3-80  
Vendor:  
"60 MZ"